Earthquake Damage to Passive Fire Protection Systems in Tall Buildings and its Impact on Fire Safety

GEOFFREY SHARP

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EARTHQUAKE DAMAGE TO PASSIVE FIRE PROTECTION SYSTEMS IN TALL BUILDINGS AND ITS IMPACT ON FIRE SAFETY

By

GEOFFREY S SHARP

Supervised by

Professor Andy Buchanan

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Department of Civil Engineering
University of Canterbury
Private Bag 4800
Christchurch, New Zealand
Phone +64-3 364-2250, Fax +64-3 364-2758

Abstract

New Zealand is a country which is extremely prone to seismic activity. One of the many impacts an earthquake may have is to cause fires. If a fire was to start in a damaged multi-storey structure the safety of the occupants would undoubtedly be in question.

During an earthquake large lateral forces are experienced by tall buildings, this in turn causes deformations to take place. It is these deformations that can cause damage to various parts of the structure. One very important component of any structure is its passive fire protection; unfortunately passive protection systems such as Gypsum plasterboard walls are very vulnerable to earthquake damage. Discovering the extent to which this reduces the fire safety of buildings is the primary objective of this project.

Currently in New Zealand there are no legislative design criteria for the event of fire following an earthquake. Another aim of this research is to gain a further understanding of this gap between the design of tall buildings for the demands of earthquake and the demands of fire. A greater understanding of the risks posed by post-earthquake fire is to be gained by addressing the vulnerability of tall buildings.

To determine the level of risk associated with post-earthquake fire the topic was split into two parts. The first part involved developing models to calculate a factor of safety for burning buildings as a ratio of available and actual escape times. The second part looked at how damage to plasterboard walls, protecting escape paths, would affect the fire safety of the building. By considering the results of these two parts an overall assessment of the risk associated with post-earthquake fire was made.

It was found that for fire following an earthquake in buildings greater than ten stories, in which the sprinklers do not operate; the occupants may be unsafe because the expected escape time is greater than the expected failure time of the fire rated walls surrounding the escape route.

Acknowledgement

I would like to acknowledge the following people who gave me the direction and encouragement to undertake this project. Without their input and guidance this project would not have been possible.

To my supervisor Andy Buchanan, thanks for enabling me to turn what was a very "woolly" research topic into something a lot more manageable. Your time was greatly appreciated.

To John Taylor, for helping me to come to terms with the requirements of the New Zealand Building Code Acceptable Solutions. Given the time restraints on this project learning how to use the document myself would have been very difficult. Also the feedback on my report you provided was invaluable.

To my friend Sarah Laird, for her time and patience while helping with the editing of this report.

Table of contents

List of Figures

List of Tables

1 Introduction

1.1 Objective

The aim of this research is to gain a further understanding of the gap between design of tall buildings for the demands of earthquake and the demands fire. Each of the two design cases have well established systems for ensuring adequate performance of a structure, but the combination of fire occurring after an earthquake currently has no legislative design criteria.

This study attempts to address the problem that is the lack of design criteria for the possibility of damage to fire protection systems which has the potential to increase the risk of casualties during a post earthquake fire. In particular looking at how tall buildings will cope in this situation. Given that there is currently no design criteria for fire after earthquake in the New Zealand building code it is the intent of this study to make some basic recommendations about further research which may in turn lead to some allowance for this scenario in future codes.

1.2 Background

The reason that there are no established methods for designing for post earthquake fire is that the concept has many unpredictable components. Firstly, not all buildings will be damaged in an earthquake so the current system of fire design will be sufficient if a fire was to start following an earthquake. Secondly, not all buildings that suffer damage in an earthquake will experience a fire. The science around predicting the likelihood of such events is so complex that it is not considered a design requirement, however given that New Zealand (Christchurch and Wellington in particular) is expected to experience a large earthquake in the foreseeable future the combination of a fire after an earthquake poses a very real danger. It seems that only by highlighting the elevated risk of casualties caused by fire after an earthquake will adequate consideration be given to implementing better design requirements in earthquake prone regions.

1.3 Outline of this Report

The initial parts of this report explain the background for carrying out the research and try to put the problem into context. The analysis is then described and explained along with the theory behind the methods used. An extensive breakdown of the results obtained through the modelling process is carried out with some conclusions and recommendations being made based on these.

1.4 Deformation Compatibility

The fundamental concept surrounding damage to a building's internal partitions during an earthquake is deformation compatibility. Internal partitions or fire cell divisions constructed from timber studs and plasterboard are erected in tall buildings using the same technique as for a single storey home. The major problem is that in a single storey house these walls form the majority of the lateral load resisting system so ensuring they are tied into the structure effectively is very important. This is done according to manuals produced by manufacturers of proprietary lining products. One such manufacturer is Winstone wallboards. They manufacture plasterboard known as Gib; of particular relevance to this study is a fire resistant product called Gib Fyreline. In the design guide published by the manufacturers they specify a certain framing system for which the board has been tested and rated, this ensures that the board performs up to the expected/tested level. This type of system is summarised in Figure 1-1.

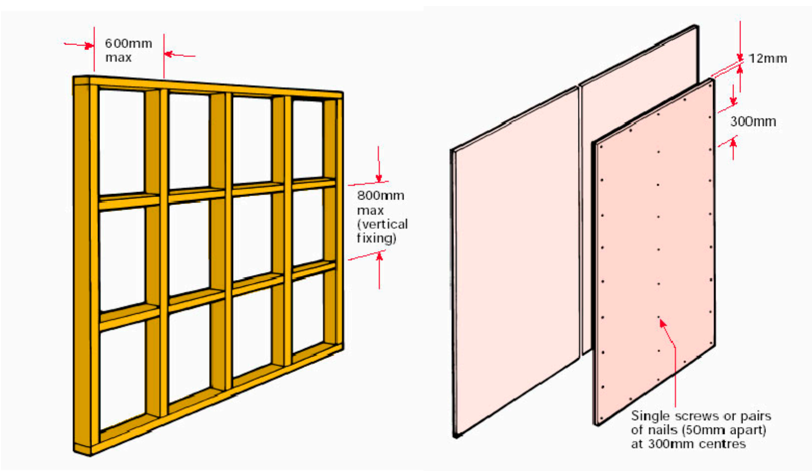
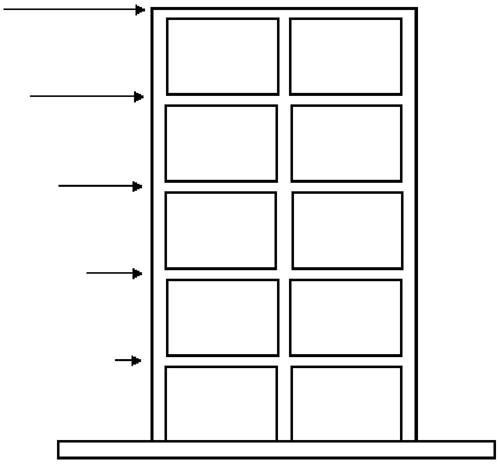
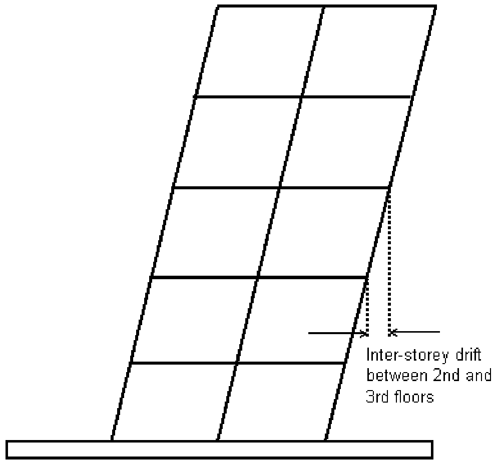


Figure 1-1 Basic timber dry-wall configuration (Winstone Wallboards, 2001)

When this passive fire protection system is installed in a multi-storey building the same method of construction is followed as for a one storey domestic dwelling. This poses some problems as the framing is often rigidly connected to both the floors above and below. Generally the plasterboard will only go as far as the false ceiling but the framing timber is fixed to the structural floor above. In the event of an earthquake the wall will suffer severe damage due to inter-storey drift. Inter-storey drift is defined as the amount of relative deflection between adjacent floors (Figure 1-2).


Frame Building showing equivalent static earthquake loads



Frame deformed under earthquake loads showing inter-storey drift under beam sidesway mechanism

Figure 1-2 Inter-storey drift for a simple five storey frame building.

The 1992 loadings code, NZS 4203 sets inter-storey drift limits in Cl 4.8.1.5 . The following limits must not be exceeded for the corresponding storey where deflections are found by either equivalent static method, modal response spectrum or elastic time history method;

0.02 (2%) for building height $\leq$15m
0.015 (1.5%) for building height $\geq$30m
Interpolate between limits for buildings between 15 and 30 m high.

This study is particularly interested in buildings less than 58 metres tall as under the current building code buildings of this height or less only require an F-fire rating (firecell rating) as opposed to a S-fire rating (structural rating) (Approved Documents Fire Safety C/AS1:2000, BIA). For the purpose of this study it will be assumed that all buildings have been designed right up to code limits, which in some cases may even be conservative. In this case a building under 15 m tall with standard 3.5 m floor heights can have inter-storey drifts of up to 70 mm while a building over 30 m tall with the same floor height may experience drifts of up to 52 mm.

Deflections calculated using elastic analysis as used in the equivalent static design method may be reduced by a scale factor of 0.85 for buildings with six stories or more. Linear interpolation is used for buildings between one and six stories high where the scale factor for a one storey building is one. For buildings with a soft storey the scale factor is always taken as 1.0. For numerical integration time history methods incorporating inelastic member response, inter-storey deflections shall not exceed 0.025 of corresponding storey height.

1.5 Method

In order to establish the significance of post earthquake fires in tall buildings the topic has been separated into two parts. The two parts can then be evaluated together to gauge the overall risk associated with the way fire safety design is carried out in New Zealand. The entire study is mainly interested in small footprint buildings typically with 10 to 15 floors. This is because this type of building is commonly used for apartments and in many cases the buildings have only a single stairway. It also helps to simplify the evacuation modelling and means that we can accurately estimate the number of people likely to be in the building at any one time.

The first part looks at how the current system for fire resistance in tall buildings copes under the recently developed "real compartment fire" scenarios. To do this the time to failure of plasterboard partitions in modern multi-storey buildings exposed to the real fire scenario will be compared with the time taken to evacuate the building. This will be done by modelling equivalent fire severity from the International Standards Organisation standard fire (which is used to give fire resistance ratings) with the severity of real compartment fires, giving a modified time to failure for the wall. This will give an indication of how long occupants have to escape the building. The factor of safety in current fire safety design under the current building code can therefore be established.

The second part of this study will look at how the earthquake and the associated inter-storey drifts will affect plasterboard drywalls in multi-storey buildings. This will be a strictly qualitative study looking at previous testing done on similar wall configurations. A progression of likely effects on plasterboard walls at different percentage drifts will be looked at; the subsequent damage at each interval can then be evaluated in terms of its effect on the fire resistant properties of the walls.

By considering both of these studies some conclusions can be drawn about the fire safety of tall buildings in New Zealand after a major earthquake. For example if the evacuation time and time to failure of a partition adjoining the main evacuation route are relatively similar (i.e. factor of safety close to 1) then any negative effect from damage caused to the partition by the earthquake will further reduce the likelihood of safe evacuation.

1.6 Previous Post-Earthquake Fires

Fires following an earthquake are a major hazard and in some cases can be more devastating than the earthquake itself. The damage caused by fires following an earthquake varies significantly, from minor damage to destruction recognised as the most damaging natural events of the twentieth century. Two such events were the 1906 San Francisco and the 1923 Tokyo earthquakes.

The San Francisco event happened at around 5 am on the 18th of April 1906 and measured 8.3 on the Richter scale and an intensity of MM IX (Modified Mercalli scale, see Appendix A). Scawthorn et al (1988) reported that the earthquake originated in the San Andreas Fault and caused 1992 $US7 billion worth of damage. Botting (1998) summarised the damage as extensive including 700 fatalities. There were 50 reported outbreaks of fire in the three hours following the earthquake which resulted in 3 days of conflagration. During this time approximately 20,000 buildings were destroyed by fire. The fires were eventually confined to a four square mile block by blasting un-burnt buildings to form a fire break. There were three main ignition sources; the first was the collapse of buildings containing fires in open fire places, lit kerosene lamps and gas lights. The second was the fracturing of electrical wiring caused by structural damage to buildings, and the final ignition source was the crossing of 550 volt, tram wires with other wires which caused sparking and arcing or working electrical appliances and circuits in nearby buildings. The earthquake itself took out the main water supply in San Francisco; this caused some major problems in terms of containing the fires. The pipelines were damaged where they crossed marshy land, totally shutting down the city wide distribution system. Due to the absence of water the fire department could do little in response to the outbreak of the fires and fires were allowed to grow rapidly and aided by a persistent wind the fires quickly grew to conflagration size.

The Tokyo event was similar in that it happened early in the twentieth century and was made worse by the primitive fire protection systems of the time. Also known as the Kanto earthquake it also measured 8.3 on the Richter scale as reported by Kenna, 1975. Fatalities were much higher with around 100,000 killed in the greater Tokyo region. Over 450,000 houses were destroyed by fire after 277 initial outbreaks. Again the loss of the main water supply occurred and as such the fires were unable to be contained.

A New Zealand example is the 1931 Hawke's Bay earthquake which measured 7.75 on the Richter scale killed in excess of 250 people throughout Hawke's Bay. Fires broke out in three locations in Napier destroying ten acres of buildings. The fire fighting effort was significantly hampered by the fact that fire engines were buried in the collapsed fire station and water mains were fractured. Fires started in three separate chemist shops where chemical vapours were ignited by Bunsen burner flames. Ruptured electrical wiring may also have caused fires to start. Overall, lack of water was the main reason for the extent of damage.

All three of the above-mentioned events took place early last century and significant developments in both fire safety design and the technology used to fight fires have been made. The alarming point though is the common theme, which is the loss of main water supplies to the cities affected. This over reliance on fire fighter intervention and the assumption that water will be available to fight fires with is still a problem today. On this basis it will be assumed that for all situations evaluated in this report that there will be no fire fighter intervention.

More recently, water mains were damaged in the 1994 Northridge Earthquake, San Francisco. Fire fighters in northern parts of San Francisco were forced to use alternative sources such as swimming pools. In terms of probability, Taylor (2003) noted that following a moderate earthquake (MMVII-MMVIII) the probability of failure of a building sprinkler system was 0.90 (increased to 0.99 for a design level earthquake). This probability was primarily based on damage to water and power supplies. This has also been highlighted by Brunsdon and Clark (2000) who commented on the vulnerability of power and water supplies in New Zealand.

2 Wellington Case Study

2.1 Background

Wellington, the capital city of New Zealand and home to over 160,000 people lies straddling a major fault. The city is bounded by the waters of Wellington harbour on one side and steep hills on the other. The central part of the city is relatively flat with the residential suburbs extending into the hilly surroundings, covering some extremely steep topography. Much of the waterfront land in downtown Wellington is reclaimed land which is particularly vulnerable to soil liquefaction during an earthquake.

The location of Wellington has meant that transport routes in and out of the city are very limited, with one route being through the steep Ngauranga gorge and the other through the Hutt valley and over the rugged Rimutaka Range (Figure 2-1). Both of these routes would be prone to landslides if a major earthquake were to hit the area. There is also major concern about the capacity of these transport routes after such a disaster given that so many people would potentially be trying to exit the city.

The reason for carrying out this case study of Wellington is to emphasise how vulnerable New Zealand buildings are to the risk of post-earthquake fire by highlighting the specific risks faced by the city.

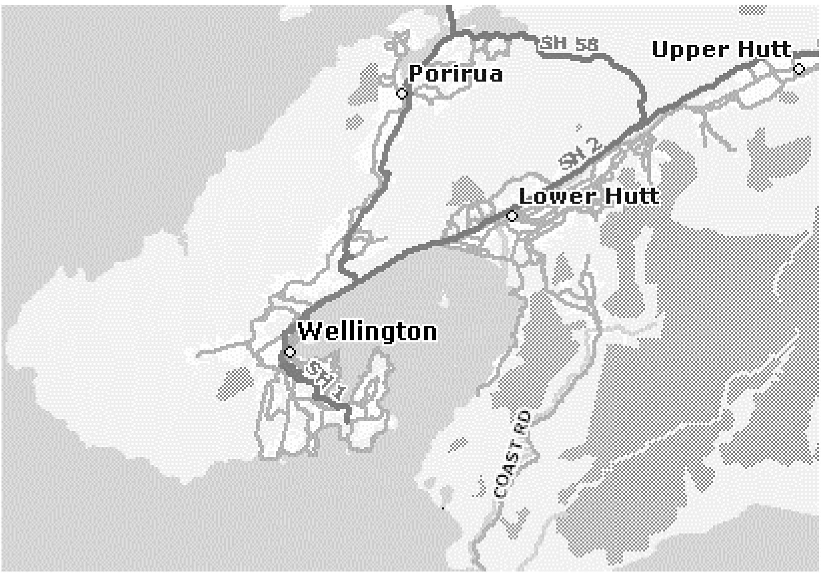


Figure 2-1 Basic map of Wellington showing the main transport routes, (New Zealand homestay website 2003)

The central city itself is very congested and given that land is at a premium there are many high-rise buildings, the majority of which are office buildings but more and more medium rise apartment style buildings are being built. Aside from the more recent buildings (1970 and newer) there are a number of un-reinforced masonry structures. These buildings will be particularly prone to heavy structural damage during an earthquake.

The compact nature of the city means that following an earthquake it is highly likely that traffic will completely gridlock meaning that emergency services will have problems getting around.

There have been two independent reports on the risk Wellington faces from earthquake. Both report casualties of between 200 and 400 people following a shallow 7.5 magnitude earthquake on the Wellington fault. Large scale damage and loss will occur over the majority of the city. Seismic hazard maps have been developed which show where the damage will be most severe.

After an earthquake the potential for fire and fully blown conflagrations to occur is very high. The main ignition sources could include electrical faults, ruptured gas lines and chemical fires. Wellington city has three pipelines used to transport hazardous materials (Wellington City Council Website). The first carries high pressure natural gas right through the city, the second diesel and light fuel oil around the port facility near to the central business district, and the third carries highly volatile aviation fuel from the port to the airport. Damage to one of these pipelines during an earthquake could cause serious a explosion or fire. Given its location and infrastructure, Wellington is a very interesting place to consider in terms of post-earthquake fire.

2.2 Geological/Seismological Background

The geological and seismic background of the greater Wellington region is very complex as shown in Figure 2-2. The basement rocks throughout the greater Wellington region are grey sandstone/mudstone sequences with some coloured mudstone conglomerate. The areas of reclaimed land are made up of domestic waste, sand boulders and rock. In the Petone and Hutt Valley areas the land is primarily swamp deposit consisting of poorly consolidated silt, mud, peat and sand (Figure 2-2)

The Wellington fault which is the primary seismic feature of the region is itself split into three main segments. This segmentation is based on past rupture history which suggests that the fault experiences movement in three individual pieces. The southern most segment is known as the Wellington-Hutt Valley segment and extends from offshore in the Cook Strait (approx 20 km south of Wellington city) to Kaitoke at the southern end of the Tararua ranges, totalling 75 km in length. The second segment of the fault runs north 55 km from Kaitoke to Putara. The final and most northern of the segments is the Pahiatua segment extending from Putara northeast to Woodville. This segment is 45 km long. North of Woodville the fault is known as the Mohaka fault (Field guide to New Zealand Active Tectonics 1994).

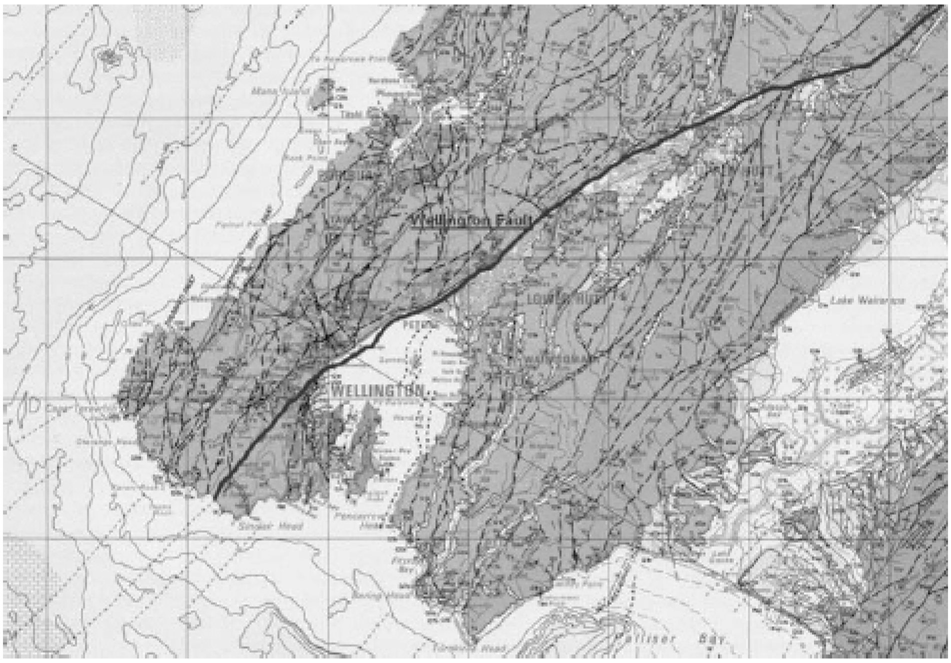


Figure 2-2 Geological map of the greater Wellington region showing position of Wellington Fault, (Institute of Geological and nuclear Sciences Website)

In addition to the Wellington fault there are two other significant fault zones that could have a large impact on Wellington city if movement was to occur along them. They are the Ohariu Fault and the Wairarapa Fault. The Ohariu Fault runs along the southern west coast from cook strait and up through the Kapiti coast. The Wairarapa Fault has two segments, one an offshore segment in cook strait which strikes approximately north east and a the main segment which extends from lake Wairarapa up through the Wairarapa depression again striking approximately north east.

2.3 Risk Analysis for Fires Following an Earthquake

There have been several comprehensive studies carried out to evaluate the potential damage that Wellington would sustain following an earthquake. For the purpose of this report two of these are particularly important. The first, a research project by Brunsdon and Clark, (2000) *Modern Multi-story Buildings and Moderate Earthquakes*. The second report of interest is by Cousins et al, (2002) *Estimating Risks from Fire Following Earthquake*.

Brunsdon and Clark were particularly interested in the effect of earthquakes on buildings and in doing so looked at the likely level of inter-storey drifts that would occur and how this may translate into both structural and non-structural damage.
The principal findings of the work by Brunsdon and Clark are as follows;

- They characterised a moderate earthquake as one which generates MM8 intensity in intermediate soils. For Wellington this translates to a magnitude 6.0 to 6.5 earthquake. This type of event has an approximate return period of 140 years and a probability of occurrence of 30% over a 50 year period.
- Inter-story drifts for a thirteen storey moment resisting frame building designed to NZS 4203:1984 in the moderate earthquake described above would range from 10 to 15mm. This indicating that both structural and non-structural damage would occur in buildings of this type in such an event.

Other major findings of the report were that damage expected in low MM scale earthquakes would cause more damage that suggested in the descriptions that accompany the lower MM scales. Also that damage ratios for modern buildings will be significantly higher than previously expected

This work was not restricted to Wellington but is important in that it underlines the expected level of damage in what is described as a moderate earthquake. The non structural damage associated with the inter-storey drifts quoted above being of particular interest to this study given that most fire partitions are non-structural.

The second report of interest, Cousins et al (2002) looks at fire as a consequence of large earthquakes. They looked at the potential for fire spread within Wellington city based on GIS (Geographic Information System) maps. The aim being to both develop working models of this spread and to help estimate potential losses associated with fires starting in different locations throughout the city and in different climatic conditions, namely wind.

Cousins et al developed two models, one static and one dynamic. The static model was primarily based around the theory of fire spread by radiant heat. They established a value of 12 metres as the maximum distance that fire could travel in order to spread across a void. The model was constructed by placing a six metre buffer around all the buildings in central Wellington and hence wherever there was an overlap between the buffers it was assumed that fire could spread. Figure 2-3 shows a portion of this static model, as can be seen groups of closely spaced buildings have the inherent potential for fire spread between them.

Figure 2-3 Static fire spread model with 12m fire spread buffers (INGS, 2002)

The second model constructed was dynamic in that it allowed for wind and was based on a far more complex map where the whole of Wellington was divided up into 10 metre by 10 metre squares. These "cells" were then designated as either combustible or non-combustible. For fire to spread a combustible cell had to come into contact with another combustible cell. This dynamic model was the main focus of the research and was developed specifically for use by the New Zealand fire service. One significant advantage of the dynamic model is that it can be run in real time. This means that actual wind speed data can be fed into the model in order to obtain actual fire spread data. The applications for this type of data are extraordinary as actual fires can be modelled in an emergency and people evacuated from the most likely path of any major conflagration.

The dynamic fire spread model developed by Cousins et al has underlined the significance of wind in the spread of fires in Wellington. To illustrate this, the model was run under four different wind conditions; calm breeze, moderate breeze, fresh breeze and near gale. The results of these four wind scenarios can be seen in Table 2-1

Table 2-1 Effect of different wind conditions on fire damage in Wellington, Cousins et al 2002.

Wind Speed	Calm	Moderate Breeze	Fresh Breeze	Near Gale
Number of buildings burnt	358	362	409	1503
Area Burnt (1000 m^2)	46	47	50	140
Loss (NZ$, millions)	87	89	100	310

2.4 Emergency Response

Following a major earthquake the emergency services in Wellington will be over stretched. The most important service as far as this report is concerned is the Fire Service. Wellington City falls in the Arapawa fire region. This region extends from as far north as Otaki and the Wairarapa and into the south island to include the Marlborough, Tasman and Nelson areas. The Arapawa fire region is comprised of 51 fire stations, 36 of which are made up of volunteers and only 15 have paid staff. Accompanying these stations are 95 fire engines and a total of 1365 staff of which only 350 are full time paid fire fighters (New Zealand fire Service website). This may seem like quite a significant number of staff however given the large size of the region and the level of devastation expected following a major earthquake resources would be pushed to the limit. For example a fire in a tall office building in downtown Wellington could require more fire fighters than the region has to offer. Fires in tall buildings require huge amount of man power to control as the fatigue imposed on fire fighters when battling a blaze after climbing stairs is immense. For example, when the First Interstate Bank Building in down town Los Angeles caught fire on the 12th floor it required over 200 fire fighters to control. This alone would totally drain the majority of the resources possessed by the Wellington City fire service. Not to mention the possibility that the cities transport system is likely to gridlock preventing easy movement of emergency services. For modelling purposes in this study the likelihood of intervention by fire fighters in a post earthquake blaze has been assumed to be nil.

3 BRANZ Deformation Report (literature review)

3.1 Background

This section of results is primarily a literature review looking at the results of some testing on timber framed, gypsum plasterboard clad walls. The report is by Deam, B.L (1997) and titled Seismic Ratings for Residential Timber Buildings, BRANZ (Building Research Association of New Zealand.) Study Report SR73.

The aim of the research was to gain a better understanding of why timber framed structures behave like they do in earthquakes. It was already well known that timber framed structures perform very well under seismically induced lateral loads, essentially due to the large number of building elements that make up the structure and the mechanism of load sharing. To make full use of these performance enhancing characteristics in a design sense the mechanics of load sharing needed to be determined. This was done by matching experimental load test data with a computer model so that the model could then be used to generate seismic response spectra.

The most relevant part of this research for this report is the experimental testing of timber framed walls. The walls that were tested under dynamic lateral loads are very similar to the walls being considered in this report. Four different walls were tested. All four were made from light timber framing and clad with gypsum plasterboard. Two of the walls had the plasterboard sheets attached horizontally while the other two walls had the sheets attached vertically. The vertical method of construction is the one most commonly used in New Zealand so the performance of these two walls was of particular interest.

The testing involved building 4.8 metre long, 2.4 metre high sections of wall. The framing was made from 100 x 50 mm timber framing, and the cladding gypsum plasterboard. The plasterboard was fixed according to manufacturers specifications. The walls were then attached to a racking rig which was used to load the walls in a cyclic fashion deflecting the walls laterally an equal distance in both directions. The wall and testing rig is shown in Figure 3-1.

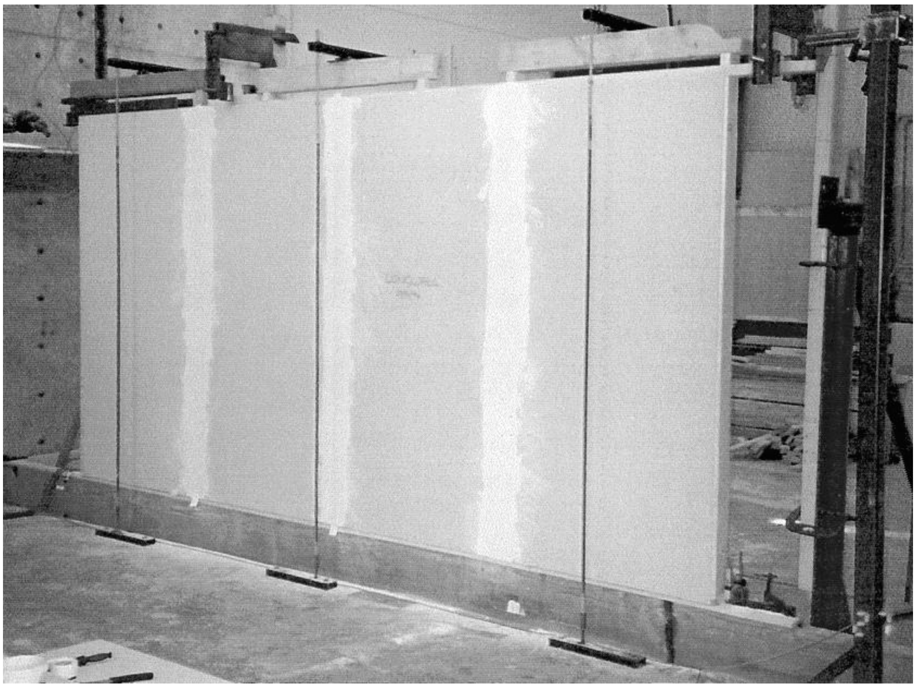


Figure 3-1 Loading rig with wall in place ready for testing, Deam B.L. 1997.

3.2 Testing Results

Of the four tests carried out only the two involving vertically oriented plasterboard sheets will be looked at.

3.2.1 Wall 1

Wall 1 was referred to as "Specimen LW2" in the BRANZ report. It was intended to be representative of wall construction normally used in New Zealand, Deam, B.L. (1997). It had four 1.2 m long by 2.4 m high plasterboard sheets attached to ex 100 x 50 framing. The plasterboard was fixed by 30 x 2.5 mm flat head nails at 300 mm centres around the perimeter of the board, and to the intermediate studs with pairs of nails spaced at 300mm.

The wall was tested over nine different cycles with the deflections ranging from ± 10mm to ± 60mm. Once the nine cycles were finished the specimen was pushed to failure. To make the results of this experiment relevant to this project the lateral deflections have been converted to percentage drift values. This means that the damage observed in these tests can be related to timber partitions in multi-storey buildings and some conclusions made about the significance of the damage for fire safety. This is based on the assumption that the walls are fixed at the top and bottom plates to the floor and ceiling of the multi-storey building. Table 3-1 is a summary of the testing carried out including the % drift applied to the specimen.

Table 3-1Loading summary for wall 1 (Speciman LW2) including % drift.

Cycle	Target Lateral Deflection mm	Measured Lateral Deflection mm	Percentage Drift Required to cause Equivalent Damage %
+1	10	9.0	0.38%
-1	-10	-9.2	0.38%
+2	15	14.2	0.59%
-2	-15	-14.6	0.61%
+3	15	14.6	0.61%
-3	-15	-15.0	0.63%
+4	30	30.6	1.28%
-4	-30	-30.6	1.28%
+5	30	31.0	1.29%
-5	-30	-31.0	1.29%
+6	60	62.6	2.61%
-6	-60	-62.1	2.59%
+7	60	62.8	2.62%
-7	-60	-62.4	2.60%
+8	60	62.9	2.62%
-8	-60	-62.1	2.59%
+9	60	62.9	2.62%
-9	-60	-62.4	2.60%

The equivalent inter-storey drifts imposed on the wall during testing ranged from 0.38% to 2.6%. This drift range is ideal for assessing the likely damage a wall in a multi-storey building may experience as the inter-storey drift limits are 2% for buildings less than 15 metres tall and 1.5% for buildings greater than 30 metres tall.

During the testing visual observations were made about damage to the wall. The descriptions were made over a range of cycles for which noticeable damage occurred.

Cycle 1 (±10mm); It was noted that there was some deformation of the plasterboard around the nails in the bottom framing plate but not other visible damage. This level of damage can be assumed to have little to no effect on the fire resistance of the wall as the minor deformation would not cause an increase in heat transfer through the wall. Given that the deformation took place on the bottom plate of the wall no smoke would be likely to penetrate any gap created around a nail as smoke would not be present that low to the ground.

Cycles 2 to 3 (±15mm); through this set of cycle's significant plasterboard deformation was observed around the nails at the top and bottom plates and in the lower region of the end studs. The largest deformations took place along the bottom plate where a 20 x 30 mm piece of plasterboard broke away adjacent to a corner nail. Some minor deformation was also noted around the nails in the intermediate studs. This level of damage is likely to have some negative impact on the way the wall behaves when exposed to fire. The corner where a piece of the board actually broke away could allow heat and flames to melt any insulation material in the inner wall and begin to degrade the plasterboard on the cold side of the wall. Also the noted deformation of the plasterboard around the nails in the top plate could mean smoke may be allowed to pass through the wall. From this it would be fair to say that at drift levels of around 0.6% the fire resistance of the wall starts to be affected.

Cycles 4 to 5 (±30mm); this set of cycles saw all of the nails in the end studs pulled through the edge of the plasterboard. Other than this there was no further damage observed. The effect of the nails pulling out of the edge of the board would mean that flames and smoke may be allowed pass through the small gap. This may not be significant enough to cause fire to spread from one room to another but by definition the fire resistance of the wall would have been compromised.

Cycles 6 to 9 (±60mm); the damage that occurred during this time was reported to be similar but more extensive than that observed in cycles 4 to 5. It was noted in cycles 4 to 5 that significant damage to cause the wall to loose its fire integrity had occurred so any further damage would exacerbate the situation.

Finally the wall was pushed to failure. The wall was racked to +290 mm, this would be an equivalent drift of 12.1 % and hence is very unlikely to occur in a multi-storey frame. The damage to the wall was extensive. The studs were pulled through the plasterboard until they were no longer attached at the bottom. The studs themselves developed significant curvature with some breaking free from the top plate. This damage can be seen in Figure 3-2.

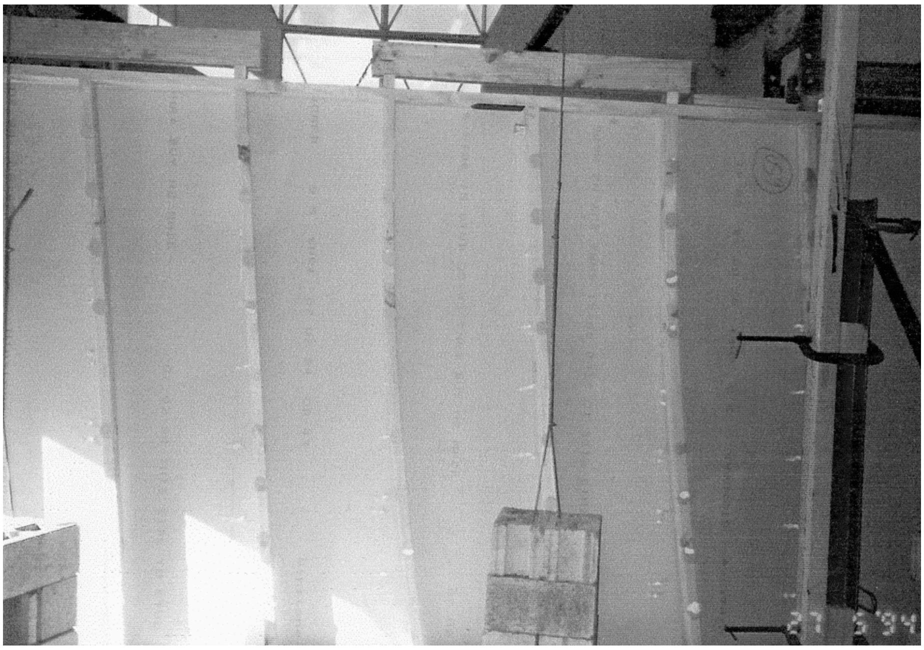


Figure 3-2 Wall 1 at failure, racked to +290 mm, Deam B.L. 1997.

3.2.2 Wall 2

Wall 2 (specimen LW3) was set up in the same way as wall one only the nails used to attach the plasterboard to the framing had proprietary steel washers around them. The wall was tested over 15 cycles ranging from 10 mm to 90 mm. A summary of the loading cycles is shown in Table 3-2.

Table 3-2 Loading summary for wall 2 (Specimen LW3) including % drift.

Cycle	Target Lateral Deflection mm	Measured Lateral Deflection mm	Percentage Drift Required to cause Equivalent Damage %
+1	10	7.0	0.29%
-1	-10	-8.3	0.35%
+2	15	11.5	0.48%
-2	-15	-13.4	0.56%
+3	15	11.7	0.49%
-3	-15	-13.9	0.58%
+4	24	20.3	0.85%
-4	-24	-22.4	0.93%
+5	24	20.6	0.86%
-5	-24	-23.0	0.96%
+6	36	33.2	1.38%
-6	-36	-30.0	1.25%
+7	36	34.9	1.45%
-7	-36	-36.0	1.50%
+8	36	35.5	1.48%
-8	-36	-35.9	1.50%
+9	36	35.6	1.48%
-9	-36	-36.4	1.52%
+10	36	35.3	1.47%
-10	-36	-36.5	1.52%
+11	36	35.7	1.49%
-11	-36	-36.4	1.52%
+12	60	59.8	2.49%
-12	-60	-72.9	3.04%
+13	60	85.2	3.55%
-13	-60	63.0	2.63%
+14	90	90.9	3.79%
-14	-90	-92.3	3.85%
+15	90	93.0	3.88%
-15	-90	-93.3	3.89%

The range of drifts experienced by wall 2 was much greater ranging from 0.29% to 3.89 %. It is unlikely that a building would experience drifts of more than 3%, so the damage that occurs to the wall in cycles 13 to 15 is not that relevant.

Cycle 1 (±10 mm); very little damage was observed around the nails for this cycle. This was because the whole wall section separated from the floor for a bout 1m at the wall end. This happened because the load applied to get the 10 mm deflection caused an uplift force greater than the gravity load applied to keep the wall in place. This means that very little can be concluded about how the damage would affect the fire resistance of the wall as it is assumed that the bottom plate would remain attached to the floor in a real building.

Cycles 2 to 3 (±15mm); some damage occurred around the nails in the bottom corners of the wall but again the uplift of the bottom plate meant very little damage. The damage that did occur would have had a similar effect to the fire resistance of the wall as was observed for cycle 1 in the first wall, that is some smoke could penetrate the wall if substantial smoke were present that close to the ground.

Cycles 4 to 5 (± 24mm); further plasterboard damage was noted around the nails. This damage was similar to that observed in wall1 such that some fire spread may occur through gaps opening up at the top and bottom plates of the wall.

Cycles 6 to 11 (±36mm); during cycle 6 the plasterboard joint between the two central sheets failed. The nails in the centre stud were pulled completely through the edge of the sheets allowing the wall to behave as two individual units for the remainder of the testing. This mode of failure does not help in terms of assessing the likely impact on the fire resistant properties of a wall in a real multi-storey building. This is because the walls in a real building are assumed to be fixed top and bottom and are not able to rock up on one corner as was observed in this test. The separated wall units can be seen in Figure 3-3.

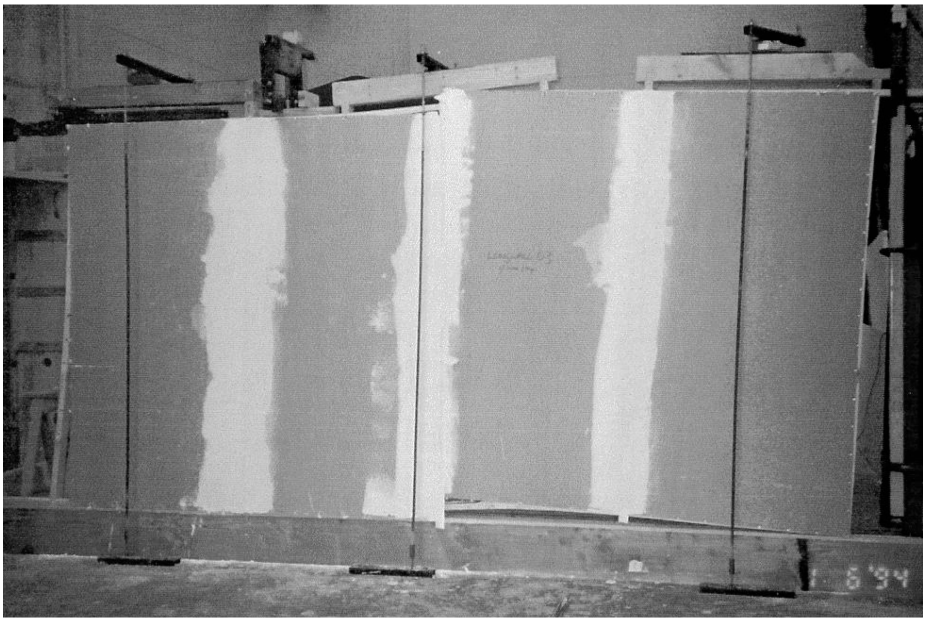


Figure 3-3 Wall 2 during the 6th cycle, showing separation into individual units, Deam B.L. 1997.

Cycles 12 to 13 (±60mm); behaviour was the same as for cycles 6 to 11 only larger deflections observed.

Cycles 14 to 15 (±90mm); the now separated wall units deformed independently with one rocking over on its corner while the other translated horizontally. The wall that translated horizontally suffered the most damage with the plasterboard being detached from the bottom half of the framing. The section of the wall that rocked over remained fairly well intact. The damage sustained by the wall that translated was extensive and would have little to no fire resistance in terms of integrity as the board was not longer attached to the framing which would allow easy spread of smoke and flames to neighbouring rooms.

As in the testing of wall 1 the wall was pushed to failure. It managed a total displacement of 150 mm; this translates to an equivalent inter-storey drift of 6.25 %. This is unlikely to occur in a real building so nothing can really be taken from the damage sustained.

3.3 Discussion

The results of these racking tests give a valuable insight into the level of damage that can be expected in timber infill walls in multi-storey buildings by representing the applied deformations from the tests as a percentage inter-storey drift.

The first wall tested had a good range of drifts applied to it given the code limits of 1.5 and 2 % from the New Zealand loadings code, NZS 4203. The damage sustained by the wall system became significant at a drift level of around 0.6%. This is where significant deformation of the plasterboard around the nails used to attach it occurred. This deformation would be significant enough to allow fire to penetrate the wall. The fact that this sort of damage can occur at such low levels of drift is somewhat alarming. The code limit for a building over 30 metres tall is 1.5 %, this is more than twice that applied to the wall for it to experience significant damage. The following cycles caused further damage and it was assumed that the wall had lost all fire resistance at a drift of 1.3%, again this is less than that specified in the New Zealand Loading code. This highlights the vulnerability of timber partitions under the current loadings code.

The second wall tested showed slightly different behaviour. In some ways the second test was not quite as valuable as the first. The deflections the wall was subjected to got up to 90 mm which is equivalent to an inter-storey drift of 3.75 % and hence is outside the allowable range from the loadings code. The behaviour of the wall was also less than ideal in that the lateral loading caused the wall to rock on one edge before the wall separated into two individual units. This was because the uplift created by the lateral load exceeded the gravity loading applied to the wall. It is assumed that in a real multi-storey structure that the wall would have significant attachment to the floors above and below it that this would not be possible. Aside from this there was still the alarming deformation around the nail lines which once pulled right out could allow the spread of smoke and flames from one compartment to another.

Both of the walls sustained enough damage to significantly reduce their fire resisting properties. This would be especially important if the wall is adjacent to an escape path from a building such as a stairwell. Full details of this testing can be found in the referenced report, Deam, B.L. (1997). *Seismic Ratings for Residential Timber Buildings.*

4 Simulation and Analysis

4.1 Spreadsheet Analysis

All of the calculations for the simulation and analysis in this study was carried out in excel spreadsheets. There were two main sheets, one for the calculation of the equivalent fire resistance of the wall assembly in question and one sheet for calculating evacuation times for the building. There were three buildings used and each building had four different scenarios. The scenarios were;

1. Building fire alarms and lighting available following an earthquake
2. Fire alarms working but no lighting (Night time)
3. Lighting but no fire alarms
4. No fire alarms or lighting available.

This meant that there were a total of 12 spreadsheets for all of the buildings and scenarios. In order to collate the data for all of the scenarios a final spreadsheet was developed and a macro written that collected all of the data from the other 12 spreadsheets. This meant that the most up to date data was collected and stored together in one spreadsheet. The macro code used to collect this data is included as Appendix #.

The basic fire situation for all of the buildings is the same. That is a fire is assumed to start on the lowest occupied floor. The occupants must evacuate to below this floor to be considered safe. The main assumptions associated with this situation are;

- Building sprinklers are not working.
- No fire fighter intervention.
- Single and double stairways become unusable once the partition between them and the fire has failed; failure is as defined in section 4.2.
- Double stairways are contained within a single shaft (scissor stairs).

4.2 Fire Resistance Ratings

A fire resistance rating (FRR) is a rating, usually expressed in units of time (minutes) of how long a certain fire resistant object can withstand exposure to the ISO 834 standard fire. The ISO 834 standard fire is used to test a certain product's fire resistance. Under the ISO fire temperature increases over time with no decay, as defined by the International Standards Organisation (ISO, 1975). The temperature, T (^{o}C) is defined as

$$T = 345\log_{10}\left(8t + 1\right) + T_o$$

Where t is the time in minutes and T_o is the ambient temperature, Buchanan, A H (2001). The standard time versus temperature curve for the ISO standard fire is shown in Figure 4-1.

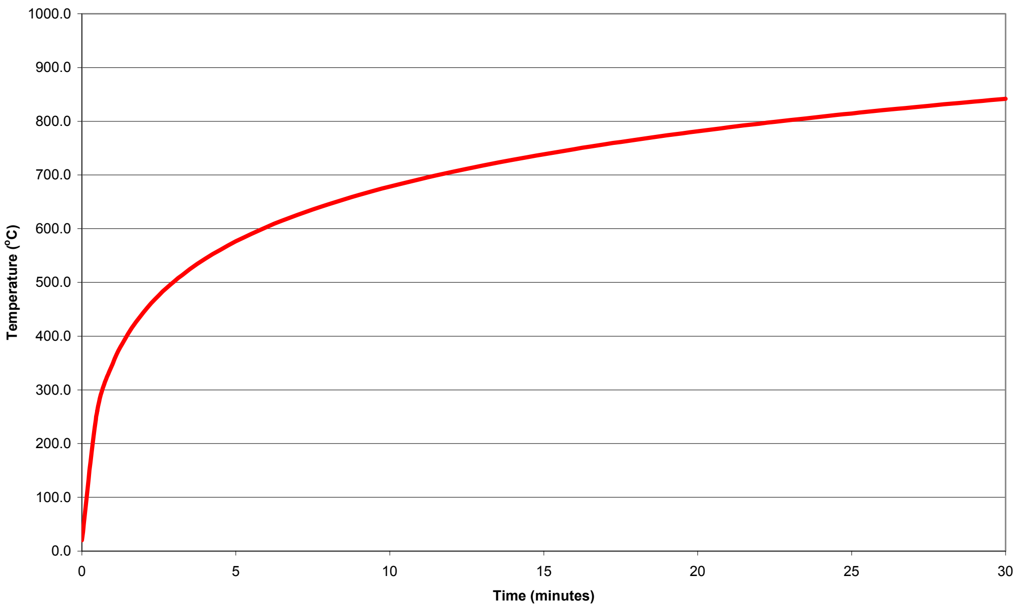


Figure 4-1 ISO 834 Standard fire time versus temperature curve for 30 minutes

It is this standard fire that is used to determine fire resistance ratings of both generic and proprietary fire protection items. A fire resistance rating has three components based on the three possible failure modes of an object exposed to fire. They are stability, integrity and insulation.

Stability is a measure of whether a structural element such as timber beam can still carry out its load resisting function. This is often determined by failure when loaded or by reaching a certain deflection limit. The rating in this case is the amount of time an element can carry out its function under exposure to the ISO fire.

Integrity is a measure of products ability to prevent fire spread from one room to another. This means that if cracks or penetrations form due to the exposure to heat then the item has failed. The rating is the time the product can be exposed to the standard ISO fire before cracks from that may compromise integrity.

Insulation is a measure of how well a barrier prevents the flow of heat; again this is primarily to avoid fire spreading from one room to another. The definition of failure is the cold side of the barrier staying below an average temperature of 140^{o}C. It is at this temperature that fire may start. So the rating in this case is a measure of how long the cold side of a barrier stays below an average temperature of 140^{o}C while exposed to the ISO fire.

Testing of passive fire protection components and systems are carried out in furnaces where the temperature can be set to follow the time versus temperature curve in Figure4-1. In New Zealand this testing is carried out at the Building Research Association of New Zealand at their testing facility in Wellington.

For the buildings in this study a FRR of 30/30/30 has been assumed. After this time it assumed that a person can no longer safely get passed the wall in question. This is a broad assumption in that the wall may experience an insulation failure which would probably not stop a person from safely getting past. The assumption is made for simplicity and is deemed fair given that current fire design deems an insulation failure to be significant.

4.3 Real Compartment fires

Although the majority of fire safety design is carried out using the ISO standard fire, more and more effort is being put into modelling what are known as “real fires”. This is because modern plastics and other composite materials are becoming more common and these products when ignited can generate much higher temperatures than are usually allowed for. This study had adopted two design fires which take into account the probability that real compartment fires may become a lot hotter than allowed for by the ISO standard fire.

The first is known as the Eurocode Parametric fire. This fire gives a time-temperature profile that allows for different fuel loads, wall lining materials and ventilation openings (Buchanan A.H, 2001). The temperature, T (^{o}C) of the fire is defined by the following equation

$$T = 1325\left(1 - 0.324e^{-0.2t^*} - 0.204e^{-1.7t^*} - 0.472e^{-19t^*}\right)$$

where t^* is a fictitious time measured in hours, given by

$$t^* = \Gamma t$$

where t is the time in hours and

$$\Gamma = \frac{\left(F_v / F_{ref}\right)^2}{\left(b / b_{ref}\right)^2}$$

where b is the square root of the thermal inertia of the compartment lining (gypsum plasterboard in this case). And F_v is the ventilation factor given by

$$F_v = A_v \sqrt{H_v / \ A_t}$$

where

A_v is the area of the window or ventilation opening (square metres)

H_v is the height of the window opening (metres)

A_t is the total internal surface area of the room (square metres)

For the Eurocode fire F_{ref} and b_{ref} are 0.04 (√m) and 1160 (Ws$^{0.5}$/m^{2}K) respectively. This definition is from Buchanan, A.H (2001), *Structural Design for Fire Safety.*

As can be seen from the definition above the temperature of the fire is highly dependant on the room geometry, including the size of any ventilation openings and the insulation of the walls. A room with well insulated walls and a large ventilation opening will experience much higher temperatures than a room with poor insulation and no ventilation.

The Eurocode parametric fire may be modelled with a decay period. This decay period starts at the end of the burning period, t_d. The burning period is defined as the time taken for all of the fuel in the compartment to be consumed. This time is directly proportional to the fuel load of the room, e_f (MJ/m^2). Fuel loads for the rooms in this study have been taken from Appendix D of the Fire Engineering Design Guide (2001). The rate at which a Eurocode fire decays depends on the duration of burning. Fires with a burning period of less than half an hour will decay at a constant rate of

625°C per hour, decreasing in a linear fashion to 250°C per hour for fires with a burning period of over two hours.

The second fire that is used for this analysis is the modified Eurocode fire. This is essentially the same as the standard Eurocode fire only the value of b_{ref} has been increased from 1160 $Ws^{0.5}/m^2K$ to 1900 $Ws^{0.5}/m^2K$. This results in significantly higher temperatures. As there is more confidence in the accuracy of the standard Eurocode fire this will be the main focus of the analysis. Figure 4-2 shows time-temperature curves for the ISO 834 standard fire, the Eurocode parametric fire, and the modified Eurocode parametric fire.

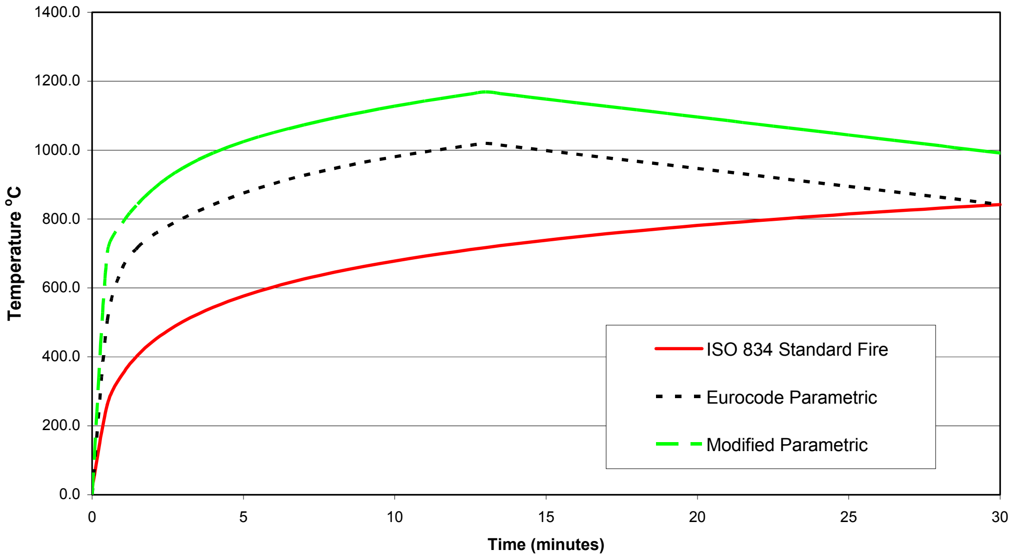


Figure 4-2 Time-temperature curve for the three design fires being used, fuel load is 300 MJ/m^2, and ventilation factor of 0.05 m$^{0.5}$.

As can be seen in Figure 4-2 the three fire curves are quite different even though the same parameters were used in the calculations. The modified parametric fire is by far the hottest reaching almost 1200 degrees Celsius. Because the duration of burning is directly proportional to the fuel load both of the parametric fires begin to decay at the same time, the ISO standard fire is independent of the fuel load hence it shows no decay period.

4.4 Equivalent Fire Severity Modelling

Fire resistance ratings are based on exposure to the ISO standard fire, however recent research has shown that in fires contained within relatively small compartments reach much higher temperatures. This means that a fire resistant system exposed to what are referred to as “real” or “compartment” fires may fail well before its specified rating time. This is because these compartment fires generate much higher heats and therefore more severe exposure. This is a major problem if the building element which fails prematurely is being relied on to ensure safe evacuation of a building’s occupants.

Testing of this theory was carried out by Nyman J.F. (2002) and some guidelines as to how to estimate the failure time of building elements exposed to real fires established. Several tests were carried out in which small compartments made of timber and light steel frames clad with plasterboard were burnt. Wooden cribs and furniture were used as fuel and the time to failure of different parts of these compartments were measured. Of the thirteen different set-ups tested all but one failed well within the time that was established during testing exposed to the ISO standard fire. Of particular interest to this project was the performance of the 30 minute rated light timber frame with gypsum plasterboard lining set-up. This wall configuration lasted 23 minutes from time of ignition compared with 42 minutes in the standard furnace test, Nyman J.F. (2002). This is around half the expected performance which poses some serious problems if it were the critical part of a fire safety design. The mode of failure in this case was insulation failure.

This testing showed that under real fire conditions building elements rated using the standard fire did not last as long as expected. From the results obtained it was established that the time to failure of non-load bearing timber drywalls could be predicted based on the equal energy area concept, Nyman J.F. (2002). Simply this means that the amount of radiant heat energy produced by the ISO standard fire in a set amount of time can be produced in a much shorter time by a real compartment fire. When a wall system is exposed to a fire the main way that damage is inflicted is by radiant heat transfer. According to basic thermodynamic theory radiant heat energy can be quantified by a function in which temperature is raised to the fourth power.

Nyman proposed that the severity of a fire can be quantified as the cumulative radiant heat energy which is applied to the wall assembly being tested. The cumulative radiant heat energy is calculated by evaluating the area under a radiant energy plot. This is expressed mathematically as,

$$area = \int_0^t Q''dt = \varepsilon\sigma \int_0^t \left(T^4\right)dt \quad \text{(KJ/m}^2\text{)}$$

where,

Q'' is the radiant heat flux incident upon the wall (W/m^2)

ε is the emissivity (conservatively assumed as 1)

σ is the Stefan Boltzman constant (5.67x10^{-8}W/m^2.K^4)

t is the time from the start of burning (minutes)

T is the compartment temperature (K)

The main benefit of this method of comparison is that any time-temperature curve can be compared to the ISO 834 standard fire test. For this study, two existing design fires will be used to approximate a real compartment fire. They are the fires mentioned in the previous section, the Eurocode parametric fire and the modified Eurocode parametric fire.

An example of this method of equivalent fire severity is shown in Figure 4-3 ; where the time to failure of a 30 minute system, as determined in the standard furnace test is compared with the theoretical time to failure when exposed to the Eurocode Parametric fire's.

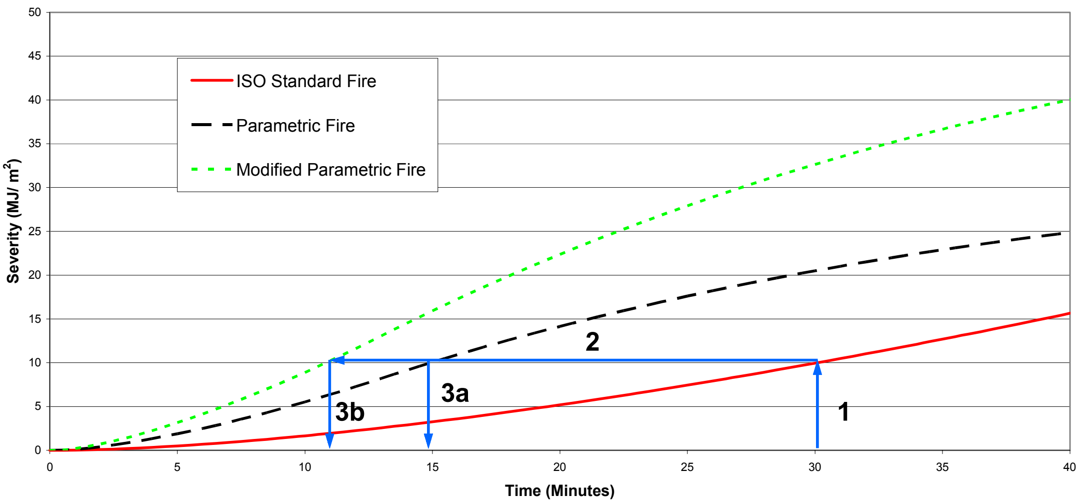


Figure 4-3 Graphical representation of the equivalent fire severity based on the equal energy area method.

The plot in Figure 4-3 show the development of fire severity based on radiant heat energy from time of ignition of the three design fires. To estimate the time to failure of a wall from a time versus severity curve such as the one shown in Figure 4-3 there is three main steps;

1. Establish the severity of the ISO 834 standard fire at the desired fire resistance rating, in the case above the FRR is 30 minutes which gives a severity of 10 MJ/m^2, this was found by taking a vertical line from the 30 minutes point on the time axis until it intercepted the ISO severity line.
2. Draw a horizontal line from the intercept with the ISO line back to the real fire curves.
3. (a) For the Eurocode failure time drop a vertical line down from the in intercept of line 2 and the Eurocode severity curve to the time axis and read off the equivalent failure time. For the above example this is 14.8 minutes.

   (b) For the modified Eurocode fire do the same but at the intercept of line 2 and the modified Eurocode severity curve. For the example above this gives an equivalent failure time of 11 minutes.

In the equivalence model used for this study this three step process was made automatic by calculating the values used to construct the chart from Figure 4-3 and then using the VLOOKUP function in Microsoft excel. The VLOOKUP function can automatically find desired values in a table of data and then return values from other columns in the table in the corresponding row. In this case the function was used to find the time at which the real fire's had the same severity as the ISO standard fire given an initial time to failure i.e. a fire resistance rating. The spreadsheets used for this calculation are included as Appendices D, E and F.

By applying this theory to each of the buildings being tested times to failure of the walls protecting the stairways were calculated. This time was assumed to be the available time occupants had to safely escape from the building.

4.5 Escape Modelling

The time taken for occupants to exit a multi-storey building is a very complex thing to model. For the purpose of this study a simplified approach will be implemented such that the effects of the earthquake on escape time can be easily adjusted and the outcomes evaluated. For example the model assumes that after an earthquake any lifts in the building will not be operational for both means of escape or for use by emergency services. The model used in this analysis uses the following assumptions:

- The fire starts on the bottom lowest occupied floor of the building
- The fire is in the compartment adjacent to the stairwell
- The partition between the stairwell and compartment is constructed from timber framing and gypsum plasterboard.
- Lifts are not operational following an earthquake
- All of the people in the building are physically able to travel down stairs unassisted and at a reasonable speed.
- The movement of people down stairs can be modelled in a linear fashion
- Only the last person on each floor is modelled as this is the most critical.
- Queuing at doorways is directly proportional to occupant density.
- The width of the stairway does not impact on the flow rate of occupants. (for simplicity, however if a particular building with an unusually wide or narrow staircase was being analysed allowances could be made)
- No intervention by emergency services such as fire fighters. (This is based on the likelihood that following a major earthquake the services will under-staffed.)

The model itself is based on an uncontrolled total evacuation as discussed in the SFPE handbook (2002). This particular way of thinking assumes that each floor of occupants is modelled as a single entity, that of the last person to leave each floor. This means that the total time for building evacuation is the time taken by the "group" of evacuees from the upper-most level in the building to reach safety. Figure 4-4 shows the escape model from the SFPE Handbook (2002) used to design the model for this study.

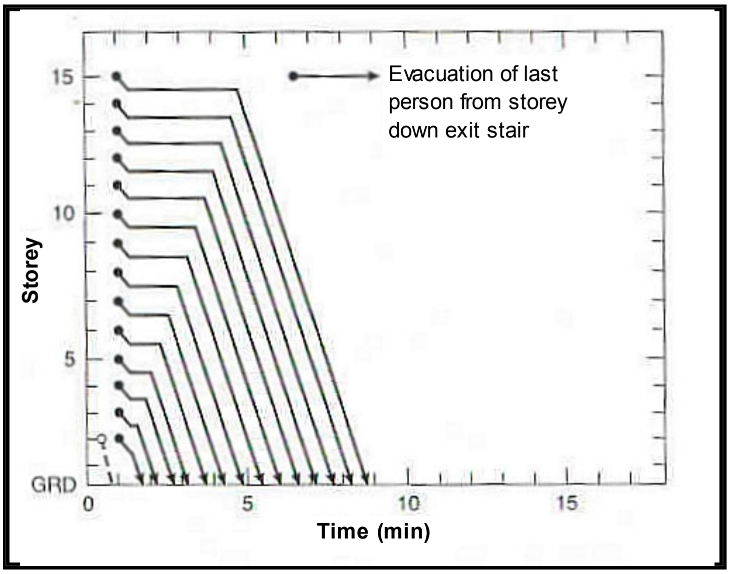


Figure 4-4 Hypothetical uncontrolled total evacuation of a 15-storey office building (SFPE Handbook, 2002)

The model takes into account the time taken for the fire to be recognised and the decision to evacuate the building to be made. There is an allowance in the model for whether alarm systems are operational after the earthquake. Once the occupants have reacted the time taken for the furthest person to reach the exit is calculated using a standard speed for moving in a relatively unconfined space of 73 metres per minute. This speed is assumed for when the evacuation takes place in daylight hours or when lighting/emergency lighting is available. When evacuation takes place in the dark this speed is significantly reduced. Because of the restricted access into a stairway there is an allowance for queuing time associated with access to the stairs. This queuing time is based on the method used in the Fire Engineering Design Guide (FEDG, 2001). The method takes into account the width of the exit and applies a boundary layer to either side of it, making the exit effectively narrower than it is. This boundary layer allows for the fact that people will be moving through a relatively narrow gap and thus cause a reduction in their travel speed.

Following the reaction time the model then allows a delay period for the evacuation of people in the floor below. This is calculated as the time taken for the occupants in the floor below to travel down two flights of stairs. This assumption was made so that each “group” of evacuees could move down the stairs unrestricted by those in front of them.

The time taken to traverse the stairs is calculated by dividing the length of stair each “group” must traverse to reach the exit level by the expected travel speed. The expected travel speed for traversing down stairs when fully lit is 30 metres per minute. This was taken from the SFPE Handbook which assumed a speed of 0.5 metres per second down the stair slope allowing approximately two treads of stair per person. Again during blackout circumstances this value was dramatically reduced in the model. This part of the model is quite optimistic in that it does not allow for people with disabilities. If occupants were impaired in any way such as blind, immobile, or elderly the travel speed would have to be significantly reduced. One of the assumptions of the model is that all occupants are of able body.

Finally as each “group” reaches the exit level of the building a further queuing delay is added to allow for passing through an exit to the street. This assumes that evacuees only have to move through one exit after the stairs. In many cases this will be conservative.

The total time for evacuation is a sum of the time taken by the top floor to reach safety. A graphical representation of the movement of each floor down the building with respect to time is shown below in Figure 4-5

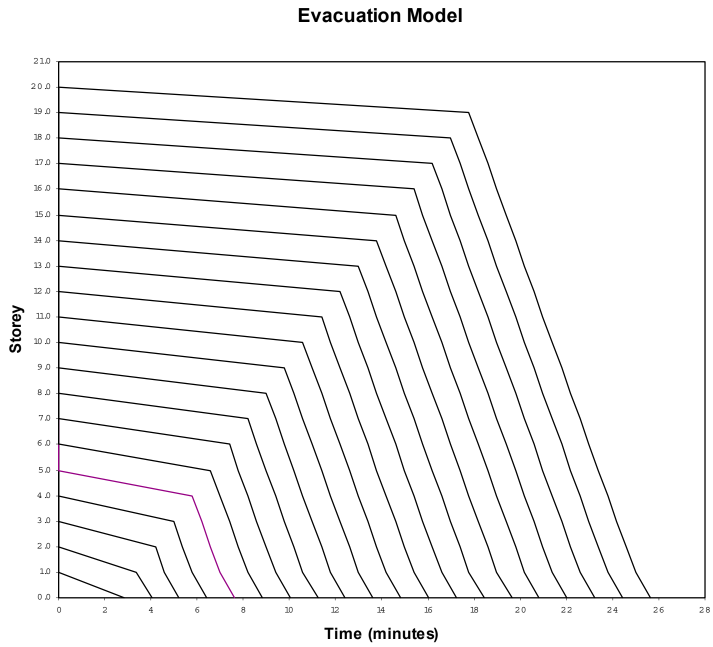


Figure 4-5 Graphical representation of simplified escape model, represents the vertical location of each "group" of evacuees with respect to time from ignition.

By looking at the movement down the building of occupants on the 20th floor of an arbitrary building we can see the various stages of evacuation. The initial, relatively shallow slope is representing the time taken from the ignition of the fire until the stairway is clear for them to descend. During this time they are assumed to actually move down one flight of stairs because in reality the occupants will not patiently wait at the top of the stairs for the people below to evacuate they will push down as far as they can. The next leg of the model shows the descent of the occupants down the stairs. Finally there is a slight kink at the bottom of the model showing the queuing time at the bottom exit.

4.6 Validity of the Model

In order to evaluate the validity of this simplified model, specific escape modelling software called Simulex was used. Simulex is a computer modelling package that is used to simulate the escape of people from large complex buildings. 3D models of multi-storey buildings can be made up base on CAD floor plans connected by staircases. Once the model of the building is loaded the user is able to define a final exit, which is the point where all occupants much reach to be considered out of the building. The software then calculates all the distances that must be travelled by occupants to escape. Occupants are placed throughout the building and then evacuation of the building is simulated. The properties of the occupants of the building are based on real life data such that people have different walking speeds and show different behaviour.

The floor plan of building 1 was used to develop an eleven story Simulex model. Once the model had been loaded 14 people were added to each floor so that the assumptions matched those made for case study building 1. Some refinement was required in terms of the way floors were linked together as some of the people became stuck during the evacuation. Results of this simulation are included in the results section of this report. A screen shot from Simulex is shown in Figure 4-6.

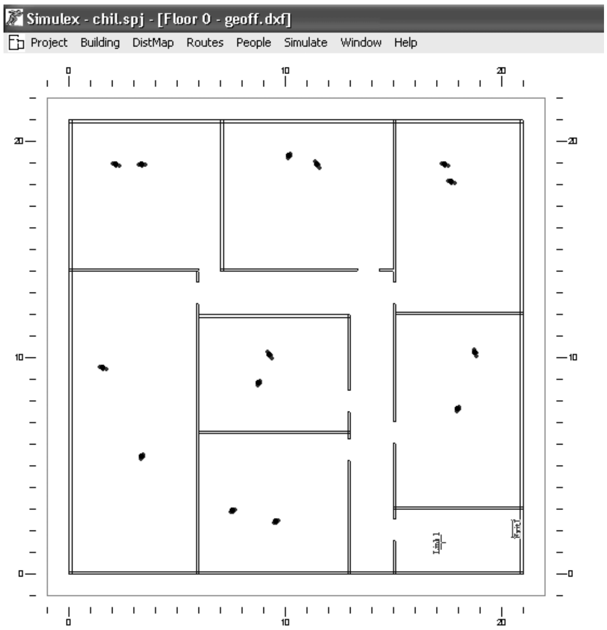


Figure 4-6 Simulex model of a typical floor in building 1.

Figure 4-6 shows the floor plan of building 1 used to construct the 3D Simulex model. The stairway is in the bottom right corner and the 14 people can be seen in the various rooms on the floor.

4.7 Case Study Buildings

In order to get a broad range of results three different building layouts and designs will be analysed. The buildings were chosen so that a broad range of scenarios could be analysed while two of the buildings are similar enough to draw conclusions about the effect of various layouts. It is assumed that the construction techniques for the timber framed gypsum plaster drywalls do not vary between buildings. All three of these buildings are based on actual designs which for the purpose of this report will remain anonymous.

The first building, referred to as “Building 1” is an eleven storey apartment building with an approximate footprint area of 450 square metres. The building has only one set of stairs. As mentioned in the description of the escape model the two lifts in the building are assumed to be out of order following an earthquake. The staircase of this building is actually on the outside of the building and open to the air so the danger of smoke filling the staircase is not an issue. The wall between the staircase and the adjacent apartment has a design Fire Resistance Rating of 30 minutes and is to be constructed from timber framing and gypsum plasterboard. Each floor has seven apartments and it is assumed that each apartment has two occupants giving a total of 14 people per floor. The model assumes that a fire starts in the apartment directly adjacent to the stairs on the lowest occupied floor and as it happens this is the kitchen of the apartment.

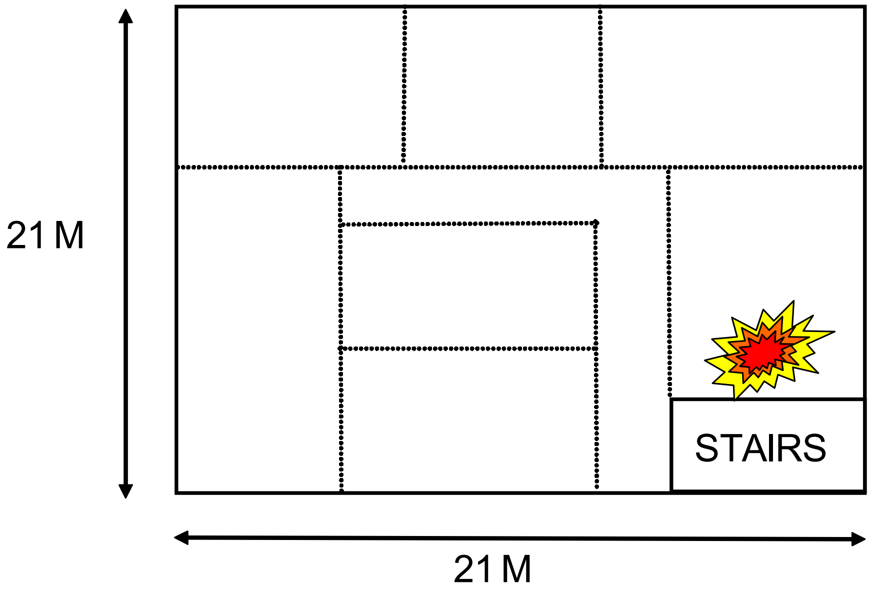


Figure 4-7 Typical floor plan of building 1, origin of fire on level 1 can be seen adjacent to the stairs.

This building was chosen as it is representative of a number of modern medium rise buildings being built in all New Zealand's main centres at the moment. Apartment buildings are more often than not made up of multiple compartments or separate cells which mean that the "compartment fire" scenario exists. The building was also chosen as apartment buildings are occupied at night when the risk of casualties in a fire are much higher due to people sleeping and lack of sufficient lighting to guide people to safety. All of these things have been taken into account. For this particular case the earthquake is assumed to take place at night. All dimensions and room details are contained within Appendix D.

The second building is referred to as "building 2". This building is also an apartment building and relies on a double stair housed in a single shaft as a means of escape. Due to the stairs being in one shaft this, means that if the shaft is penetrated by fire then both stairs are assumed to become unusable at the same time.. The building is 16 stories tall of which the top ten are used for apartments. The bottom six storeys are used for car parking. The street level escape is located on the fourth floor however for this study the occupants only need to get themselves below the level which the fire is on. Again the fire is assumed to start adjacent to the stairwell on the lowest occupied floor (level seven).

Each occupied floor has a total of nine units with varying occupant numbers. Based on the number of beds there are assumed to be a total of 36 people per floor. This gives a total of 360 people that need to be evacuated. The maximum distance that any one evacuee needs to travel on a floor to reach the stairs is 20 m. the internal walls between the stairs and the apartments are constructed from timber framing and gypsum plasterboard. A Fire Resistance Rating of 30 minutes has been assigned to these walls. To make the necessary fire calculations some assumptions about the ventilation in the apartment where the fire starts have been made. The only opening is a sliding door that accesses a small decking. The full dimensions and details are included in Appendix E. The approximate layout of building 2 is shown in Figure 4-8.

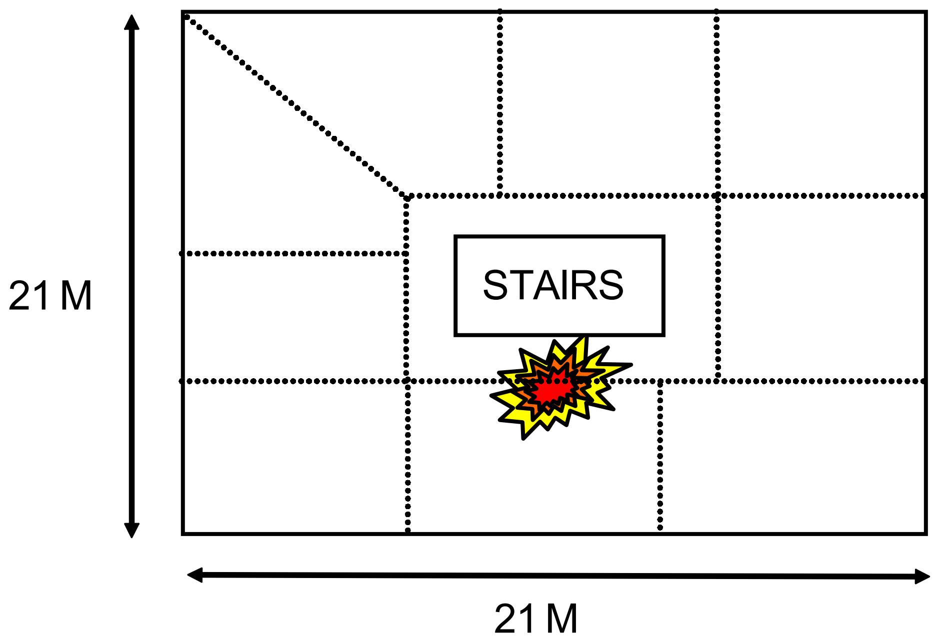


Figure 4-8 Typical floor plan of building 2, origin of fire on level 6 can be seen adjacent to the stairs.

Because both building's 1 and 2 are medium rise apartment buildings comparisons can be made where they differ in physical layout. The first major difference between building 1 and 2 is that building two has the potential to house a lot more people. This means that by comparing the outcomes of the models some conclusions about occupancy rates can be made. The next major difference is that the double stairwell in building 2 can accommodate twice as many people as the single stairwell in building 1. Also the stairs are located in different positions, for building 1 they are situated on the outside of the building and are not enclosed. The stairs in building 2 are located in the centre of the building. This has two effects; the first is that the average distance travelled by occupants to get to the stairs is less for building 2. The second effect is that for building two there is potential for smoke penetration into the stairs.

The third building is a 16 storey office building and is referred to as “building 3”. The building is assumed to have 90 occupants per floor and is open plan in nature. The fact that the building is open plan means that some major assumptions about the design fire have to be made. The large open plan area of this office space is much larger than the other two buildings so the validity of using the compartment fire model is questionable. So that there is continuity throughout the study it is assumed that the compartment fire model can be used with the following assumptions;

- The entire area of the office is assumed to act as two fire compartments; this is assuming that the stairs and other services in the centre of the building act as a partition splitting the building floor plan in two.
- Only a portion of the windows nearest to the fire will shatter to provide ventilation to the fire. This was assumed to be 2/3’s of the windows on the wall closest to the fire at ignition.

The building has a typical floor area of 936 square metres. The greatest distance an occupant must travel to reach the stairs is 20 metres. Because of the number of occupants and height of the building it is assumed that there is a double staircase in the centre of the building. As for building two the stairs are assumed to be in a single shaft. This is for simplicity as it is assumed that if the stair shaft is penetrated by fire both of the staircases become unusable. Because the building is only 16 stories it has an effective escape height of less than 58 metres therefore the fire resistance rating required for the partition between the stairs and the rest of the building is only 30 minutes. The typical floor plan is shown in Figure 4-9.

Figure 4-9 Typical floor plan for building 3, origin of fire on 1st floor shown in lower half of plan area.

This building was chosen for a number of reasons. The first is that the previous two buildings are residential in nature and hence will only really be full outside of standard working hours. This building therefore represents the risks associated with a medium rise office building. One advantage this building has is that it will not be affected by the loss of lighting as it assumed that there will be sufficient natural light during operating hours for people to escape. For the scenarios where there is assumed to be no lighting it is assumed that there is only five people on each floor.

Another reason for choosing this building was that is had a large number of occupants so valuable conclusions about evacuation time and the number of occupants per floor can be made.

All of the buildings fall within the Acceptable Solution C/AS1 for fire design as part of the New Zealand Building Code. All of the buildings have an escape height of less than 58 metres which allows them to only require 30 minutes of protection to the escape routes.

4.8 Timber Wall Configuration

The critical part of the fire design for this study has been assumed to be the survival of the timber drywalls between the fire and the stairs. All of these walls were assumed to have been built in accordance with the New Zealand Building code and made up of proprietary components as specified in the “Gib Fire Rated Systems” catalogue. The catalogue is published by Winstone Wallboards Ltd, 2001.

5 Results

5.1 Verification of Escape Model Using SIMULEX

Several runs of the simulation were carried out to get a good approximation of the random evacuation of the eleven storey apartment building. The overall evacuation took 14 minutes and 33 seconds. There were several observations made during the period of evacuation;

- The people rushed for the exits initially causing major blockages around the entrances to stairwells.
- Some of the slower occupants held up the progress of the majority of the occupants
- When slow people were in the stairs they were often passed by faster people this often resulted in blockages as there was not enough room in the stairs for this passing manoeuvre to take place.

Overall the simulation seemed to be a good approximation of an unorganised simultaneous evacuation of a multi-storey building. The output text file from this simulation is included as Appendix C.

5.2 Building 1, (11 storey apartment building)

The modelling of building 1 involved four different scenarios. The four scenarios were;

1. Post earthquake fire where the buildings alarm system was fully operational and sufficient emergency lighting was available to help people escape.
2. Post earthquake fire with alarms working but no emergency lighting
3. Post earthquake fire without alarm systems or emergency lighting.
4. Post earthquake fire where the buildings alarm system was not working due to damage or interference from the earthquake but still sufficient lighting to aid escape.

The first scenario involved a fire starting on the ground floor of the building adjacent to the stairwell. The fire rating of the partition separating the stairs and the fire was 30 minutes. By the method of equivalent fire resistance outlined in section 4.4 the partition would last only 14.5 minutes when exposed to the Eurocode parametric fire and 10.5 minutes when exposed to the Modified Eurocode parametric fire. For this study the results of the buildings under the Eurocode fire are deemed to be the most important. Therefore the time occupants have to get from their respective floors to the ground floor exit is 14.5 minutes. It is assumed that after this time the partition between the fire and stairs is compromised by any of the failure modes described in section 4.2.

The escape time for this first scenario was 15 minutes. This time includes some allowance for recognising the alarm and deciding what action to take. Because the time taken to escape exceeds the time to failure of the partition between the fire and the stairs the factor of safety was 0.97 (where factor of safety = time available for safe escape / time actually taken to escape). From the escape model it was determined that at time of failure of the wall there was still one whole floor still to be evacuated. This meant a total of fourteen people were put at risk.

Scenario two had the same failure time for the wall as in scenario one. The escape time was 27.8 minutes. This included 5 minutes of reaction time by the occupants due to alarm failure. Given this escape time a factor of safety of 0.52 resulted. Using the escape model at time of failure of the wall approximately 6 floors remained un-evacuated. This amounted to 84 people being put at risk.

In scenario three it took 31.67 minutes to evacuate the building which gave a factor of safety of 0.46. Again the escape included 5 minutes of reaction time but also the travel speed of the occupants was assumed to halve due to their being insufficient lighting. At the time of failure of the wall in question there were still 8 floors to be evacuated. This resulted in 112 people being put at risk.

Scenario four saw a total evacuation time of 18.9 minutes. This yielded a factor of safety of 0.77. This left four floors unable to be evacuated, and resulted in 56 people being put at risk.

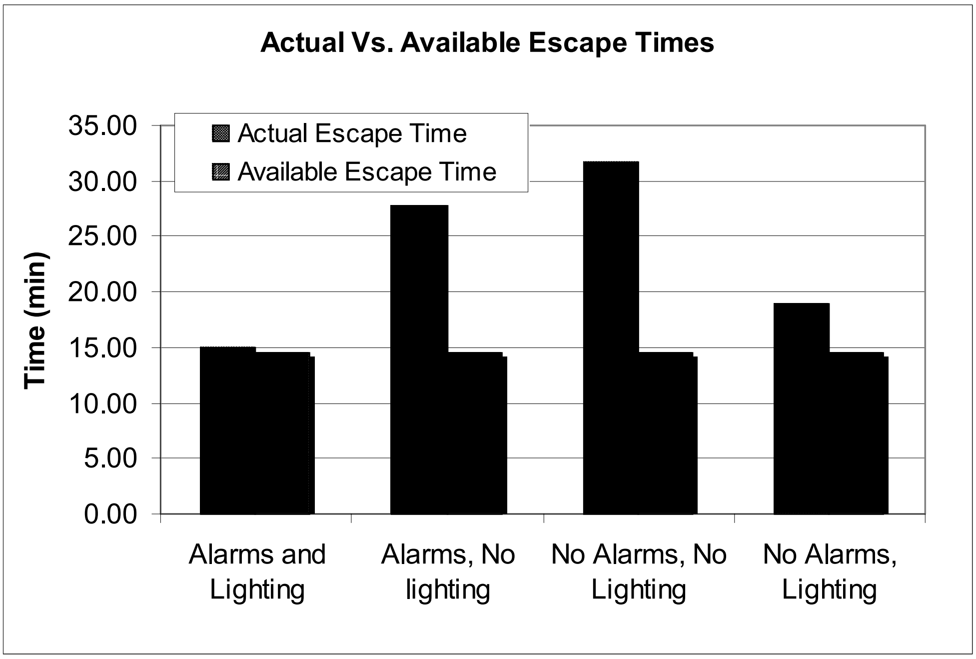


Figure 5-1 Actual escape times compared with available escape times for building 1.

Figure 5-1 is a summary of the results from the four scenarios tested for building one. The spreadsheets used to calculate this data are included as Appendix D. All design assumption, dimensions and fire design fire parameters are included in the spreadsheets.

5.3 Building 2, (16 storey apartment building)

Building two was modelled under the same four scenarios as for building one.

Again the specified fire resistance rating of the partition was 30 minutes. Exposed to the Eurocode parametric fire it lasted for only 16.5 minutes and exposed to the modified Eurocode fire it lasted 12 minutes. Again the results of the Eurocode fire are the most important.

In scenario one, the total evacuation time for the building was 8.7 minutes. This is significantly less than that found for building one, probably a result of the double stair. As the time to failure of the critical wall exceeded the time taken for full evacuation the factor of safety was found to be 1.9. Because the factor of safety was greater than one it is assumed that everyone from the building safely escaped. This assumption does not allow for any of the expected reduction in failure time caused by the physical degradation of the wall by the earthquake.

In scenario two it took 14.58 minutes to evacuate the building. This gave a factor of safety of 1.13. Again no people were put at risk in this scenario.

Scenario three had an evacuation time of 18.48 minutes. This gave a factor of safety of 0.89. At the time of failure of the critical wall approximately 2 floors remained un-evacuated. As there were assumed to be 36 people per floor a total of 72 people were put at risk under this scenario.

The fourth scenario had an evacuation time of 12.6 minutes; this yielded a factor of safety of 1.31. This means that no one was put as risk under this scenario.

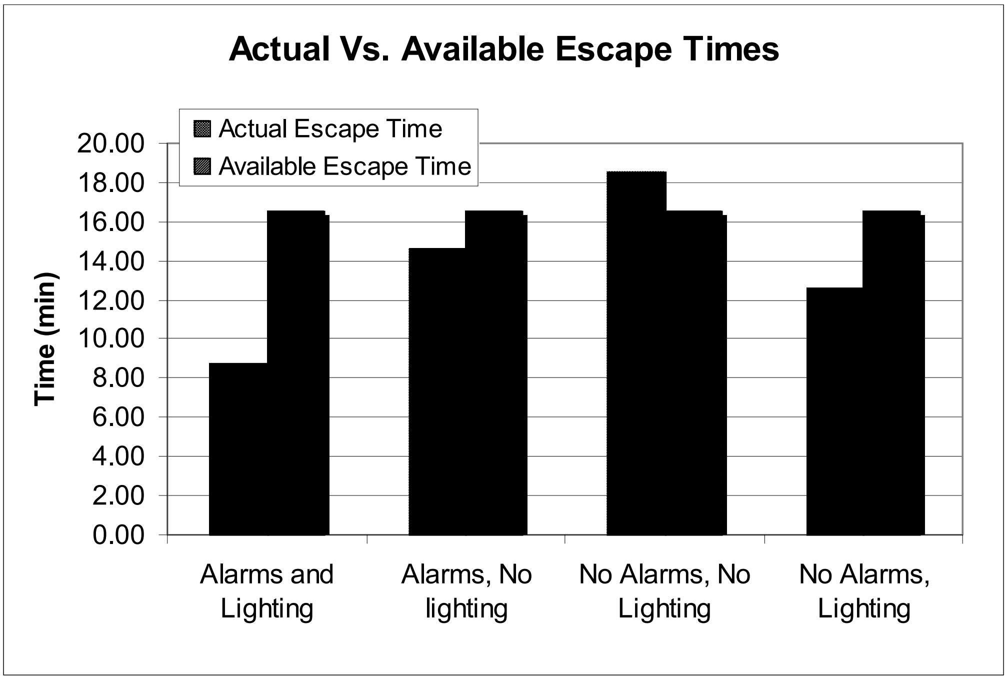


Figure 5-2 Actual escape times compared with available escape times for building 2.

Figure 5-2 is a summary of the actual and available escape times. It shows that only under scenario 3 are any of the occupants of the building at risk. The spreadsheets used to calculate this data are included as Appendix E. All design assumption, dimensions and fire design fire parameters are included in the spreadsheets.

5.4 Building 3, (16 storey office building)

Building three was modelled under the same four scenarios as buildings one and two. The only difference is that the number of occupants was adjusted for the scenarios where there were no lights. This is because the building is assumed to have very few occupants during the dark, night hours.

The design fire resistance rating of the wall between the fire and the stairs was 30 minutes. The equivalent time to failure when exposed to the Eurocode parametric fire was 17.5 minutes. When exposed to the modified Eurocode parametric fire the wall was expected to last 12.5 minutes.

For scenario one the evacuation time was 14.15 minutes, this gave a factor of safety of 1.24. It was expected that there would be no people put at risk under this scenario.

Under scenario two the evacuation time was 20.72 minutes. This gave a factor of safety of 0.84. Three floors remained un-evacuated at time of failure of the critical wall. Because this scenario was assumed to take place at night only five people were assumed to be on each floor so the total number of people put at risk in this scenario was limited to 15.

Scenario three saw an evacuation time of 27.6 minutes. This gave a factor of safety of 0.63. This meant that approximately 9 floors were not able to be evacuated. Again this scenario took place at night so the total number of people put at risk was 45.

Scenario four had a total evacuation time of 16.05 minutes. For this a factor of safety of 1.09 was achieved. In this case no people were put at risk as the time taken to escape was less than the failure time of the critical partition.

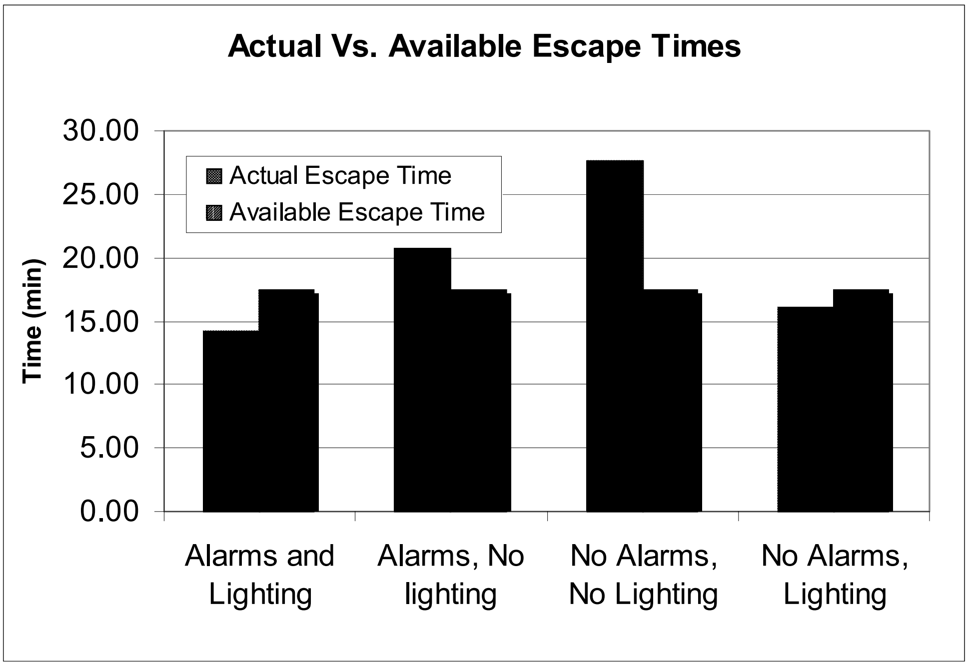


Figure 5-3 Actual escape times compared with available escape times for building 3.

Building three was only unsafe for the night time evacuations as shown in figure 5-3. The spreadsheets used to calculate this data are included as Appendix F. All design assumption, dimensions and fire design fire parameters are included in the spreadsheets.

6 Discussion of Results

From the results of the spreadsheet analysis it is obvious that the most dangerous building was the 11 storey apartment building. All four of its scenarios achieved a safety factor of less than 1. This essentially means that the building is unable to be safely evacuated in any of the scenarios. The first building is critical as it has only a single stair.

The second building (16 storey apartment building) was slightly more conservative as far as its results were concerned. Of the four scenarios tested only the worst case, scenario 3 resulted in a safety factor of less than 1. This showed that if an apartment building had two stairs that the chance of people being put in danger was significantly decreased. The other item that may have lead to the greater safety factor was that the stairs were located in the centre of the building as opposed to on the outside wall. This meant that the distance travelled by each of the escapees was less hence a reduction in the time taken to evacuate the building.

The third building (16 storey office building) showed fairly similar results to the second building in that the only scenario with a safety factor of less than 1 was when the lighting was assumed to have been lost. Again in this case the building had a double stair which helped to minimise escape time. The number of people actually put at risk in scenarios two and three is limited because it is an office building these scenarios can only take place at night when there would be very few people in the building.

The four different scenarios used for this analysis involve a very diverse range of situations. The first scenario is the most probable in that it assumes that the building alarm systems are operational and that there will be sufficient light for the occupants to escape. This is fair considering that it is highly unlikely that an earthquake will cause sufficient damage to cause an electronic alarm system to fail. Emergency lighting is also likely to be available given that it is a requirement under C/AS1, the acceptable solutions for fire design in the New Zealand building code that multi-storey buildings have battery powered emergency lighting in the emergency exits.

The second and third scenarios are definitely worst case scenarios as they both assume loss of emergency lighting. The chance that loss of lighting would occur is highly unlikely as mentioned above.

The fourth scenario is less likely than the first but not totally inconceivable. The chance of an alarm system failing is highly unlikely however there may still be situations where people become unresponsive to the alarm. One such situation may occur if the earthquake itself causes a false fire alarm, if once back inside the building the occupants hear another alarm they may presume that it is another false alarm.

One situation that is not considered by the scenarios above is the possibility that following a large earthquake all of the buildings occupants decide to leave the building regardless of whether there is a fire. This is less likely to happen during the night but is still possible. In contrast to this a fire may not start following earthquake for quite some time, and if people had initially left a building following the earthquake they might return before a fire has even started.

The escape models used do not take account of damage that may actually restrict safe passage of the occupants. Major internal damage may jam doors or cause large objects to block narrow passages. This situation is nearly impossible to quantify so it has been conservatively omitted from the model.

Failure of a plasterboard wall by insulation may not increase the risk of injury to people trying to escape past the wall. A section of wall becoming hot is not likely to make a stairwell unusable. The two modes of failure which are most critical for protecting escape paths are stability failures and integrity failures.

To gain a more conclusive insight into the overall fire safety of these buildings following an earthquake it is necessary to consider the impact of seismic damage to the critical timber partitions. Of the twelve scenarios (four for each building) nine returned a factor of safety of close to or less than one. For any of these cases the physical damage caused by the earthquake to the walls will only serve to exacerbate the potential for injury. If it is assumed that the earthquake causes inter-storey drifts of around 0.7 % then significant damage would occur and result in the fire resistance of the wall being reduced as mentioned in section 3.3. This may mean that each of the three buildings is then faced with at least one dangerous scenario even when emergency lighting is assumed to be working.

7 Conclusions

- For fire following an earthquake in buildings greater than ten stories, in which the sprinklers do not operate; the occupants may be unsafe because the expected escape time is greater than the expected failure time of the fire rated walls surrounding the escape route.

- Safety is further decreased if alarms and/or emergency lighting do not operate.

- Buildings with a single stair are particularly vulnerable.

- Safety would be greatly increased if the Building Code required structural (S) ratings for all buildings less than 58 metres high. In the current approved document only buildings above this height require S ratings. Buildings between 30 and 58 metres tall are particularly vulnerable as they only require an F rating of 30 minutes of fire resistance protecting the exit routes. The results of the analysis carried out suggest that by increasing this rating to 60 minutes much of the risk would be eliminated.

The above conclusions assume no damage to the plaster board walls surrounding the exits.

- The way in which plasterboard walls are constructed in multi-storey buildings makes them especially prone to damage when lateral deformations take place which will result in a further decrease in safety. Where these relatively weak partitions are attached directly or indirectly to the floor above and below they can experience severe drifts and hence major damage. A new less rigid way of attaching these sheets may be one way to mitigate the damage caused. Finding a system that is “flexible” and fire resistant may prove difficult.

- The damage sustained by plasterboard walls when exposed to lateral loads is fairly localised. The damage is mainly seen as deformation of the board material around the nails used to attach the sheets to the timber framing. It appears that this is not likely to cause the board to actually detach from the framing but its performance as a fire resisting element becomes highly questionable. Damage starts to affect the performance of a fire resisting wall at drifts of around 0.6 %. This a major concern given that the New Zealand loadings code NZS 4203 1992 allows 1.5 % to 2.0% drift depending on storey height.

8 Recommendations for Further Research

- To get a full understanding of how structural damage to plasterboard will affect its fire resistance some experimental testing may be beneficial. To rack a full scale plasterboard wall and then test it in a furnace would provide some valuable information for any future studies of this nature.
- Alternative methods for attaching the plasterboard sheets to the framing could be investigated such that a degree of lateral movement is catered for. This could only be used in multi-storied buildings where the walls do not form part of the lateral load resisting system.
- Further testing and verification of the equivalent fire severity methods used in this project could be carried out. Room dimensions could be varied to see if the method can be applied to much larger compartments. The theory could also be tested on wall configurations other than just plasterboard, light pre-cast concrete walls may be one.
- Testing of racked plasterboard walls for smoke penetration could be done. The purpose of this would be to evaluate the risk of smoke penetrating escape routes because of seismic damage to plasterboard walls.

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10 Appendix A; Modified Mercalli Earthquake Intensity Scale

I. People do not feel any Earth movement.

II. A few people might notice movement if they are at rest and/or on the upper floors of tall buildings.

III. Many people indoors feel movement. Hanging objects swing back and forth. People outdoors might not realize that an earthquake is occurring.

IV. Most people indoors feel movement. Hanging objects swing. Dishes, windows, and doors rattle. The earthquake feels like a heavy truck hitting the walls. A few people outdoors may feel movement. Parked cars rock.

V. Almost everyone feels movement. Sleeping people are awakened. Doors swing open or close. Dishes are broken. Pictures on the wall move. Small objects move or are turned over. Trees might shake. Liquids might spill out of open containers.

VI. Everyone feels movement. People have trouble walking. Objects fall from shelves. Pictures fall off walls. Furniture moves. Plaster in walls might crack. Trees and bushes shake. Damage is slight in poorly built buildings. No structural damage.

VII. People have difficulty standing. Drivers feel their cars shaking. Some furniture breaks. Loose bricks fall from buildings. Damage is slight to moderate in well-built buildings; considerable in poorly built buildings.

VIII. Drivers have trouble steering. Houses that are not bolted down might shift on their foundations. Tall structures such as towers and chimneys might twist and fall. Well-built buildings suffer slight damage. Poorly built structures suffer severe damage. Tree branches break. Hillsides might crack if the ground is wet. Water levels in wells might change.

IX. Well-built buildings suffer considerable damage. Houses that are not bolted down move off their foundations. Some underground pipes are broken. The ground cracks. Reservoirs suffer serious damage.

X. Most buildings and their foundations are destroyed. Some bridges are destroyed. Dams are seriously damaged. Large landslides occur. Water is

thrown on the banks of canals, rivers, lakes. The ground cracks in large areas. Railroad tracks are bent slightly.

XI. **Most buildings collapse. Some bridges are destroyed. Large cracks appear in the ground. Underground pipelines are destroyed. Railroad tracks are badly bent.**

XII. **Almost everything is destroyed. Objects are thrown into the air. The ground moves in waves or ripples. Large amounts of rock may move.**

11 Appendix B; Visual Basic for Applications Code, Data Retrieval Macro.

```
Sub Retrieval()
'
' get_num Macro

'Macro written by: Geoff S. Sharp 14/8/03

'This macro was created to retrieve data from 12 different
'spreadsheets. This meant that the most up to date data was
'used. It made it a lot simpler to keep track of any
'changes made to the scenario spreadsheets.

'get ISO 834 Fire time to failure
    ChDir "C:\Documents and Settings\Geoff Sharp\My Documents\Project\Building 1"
    Workbooks.Open Filename:= _
        "C:\Documents and Settings\Geoff Sharp\My Documents\Project\Building
     1\A,L.xls"
    Windows("Results.xls").Activate
    Range("B10").Select
    ActiveCell.FormulaR1C1 = _
        "='[A,L.xls]Main Calcs'!R22C13"

'get Eurocode time to failure
    Range("B11").Select
    ActiveCell.FormulaR1C1 = _
        "='[A,L.xls]Main Calcs'!R23C13"

'get Mod. Euro duration
    Range("B12").Select
    ActiveCell.FormulaR1C1 = _
        "='[A,L.xls]Main Calcs'!R24C13"

'get floor num
    Range("B14").Select
    ActiveCell.FormulaR1C1 = _
        "='[A,L.xls]Simple escape model'!R10C2"

'get people/floor
    Range("B15").Select
    ActiveCell.FormulaR1C1 = _
        "='[A,L.xls]Simple escape model'!R11C2"

'get evac times

            'A,L
                Range("B19").Select
                ActiveCell.FormulaR1C1 = _
                    "='[A,L.xls]Simple escape model'!R45C2"

            'A,NL
            ChDir "C:\Documents and Settings\Geoff Sharp\My
     Documents\Project\Building 1"
                Workbooks.Open Filename:= _
                    "C:\Documents and Settings\Geoff Sharp\My
     Documents\Project\Building 1\A,NL.xls"
                Windows("Results.xls").Activate
```

```
            Range("C19").Select
            ActiveCell.FormulaR1C1 = _
                "='[A,NL.xls]Simple escape model'!R45C2"

        'NA,NL
        ChDir "C:\Documents and Settings\Geoff Sharp\My
Documents\Project\Building 1"
            Workbooks.Open Filename:= _
                "C:\Documents and Settings\Geoff Sharp\My
Documents\Project\Building 1\NA,NL.xls"
            Windows("Results.xls").Activate
            Range("D19").Select
            ActiveCell.FormulaR1C1 = _
                "='[NA,NL.xls]Simple escape model'!R45C2"

        'NA,L
          ChDir "C:\Documents and Settings\Geoff Sharp\My
Documents\Project\Building 1"
            Workbooks.Open Filename:= _
                "C:\Documents and Settings\Geoff Sharp\My
Documents\Project\Building 1\NA,L.xls"
            Windows("Results.xls").Activate
            Range("E19").Select
            ActiveCell.FormulaR1C1 = _
                "='[NA,L.xls]Simple escape model'!R45C2"

'Get floors at risk figures

        'A,L
            Range("B21").Select
            ActiveCell.FormulaR1C1 = _
                "='[A,L.xls]Simple escape model'!R55C2"

        'A,NL
        ChDir "C:\Documents and Settings\Geoff Sharp\My
Documents\Project\Building 1"
            Workbooks.Open Filename:= _
                "C:\Documents and Settings\Geoff Sharp\My
Documents\Project\Building 1\A,NL.xls"
            Windows("Results.xls").Activate
            Range("C21").Select
            ActiveCell.FormulaR1C1 = _
                "='[A,NL.xls]Simple escape model'!R55C2"

        'NA,NL
        ChDir "C:\Documents and Settings\Geoff Sharp\My
Documents\Project\Building 1"
            Workbooks.Open Filename:= _
                "C:\Documents and Settings\Geoff Sharp\My
Documents\Project\Building 1\NA,NL.xls"
            Windows("Results.xls").Activate
            Range("D21").Select
            ActiveCell.FormulaR1C1 = _
                "='[NA,NL.xls]Simple escape model'!R55C2"

        'NA,L
          ChDir "C:\Documents and Settings\Geoff Sharp\My
Documents\Project\Building 1"
            Workbooks.Open Filename:= _
                "C:\Documents and Settings\Geoff Sharp\My
Documents\Project\Building 1\NA,L.xls"
```

```
                Windows("Results.xls").Activate
                Range("E21").Select
                ActiveCell.FormulaR1C1 = _
                    "='[NA,L.xls]Simple escape model'!R55C2"

'Closing opened workbooks
Windows("A,L.xls").Close

Windows("NA,L.xls").Close

Windows("NA,NL.xls").Close

Windows("A,NL.xls").Close

Windows("Results.xls").Activate
End Sub
```

12 Appendix C; SIMULEX Model of Building 1, Output File

```
Number of Floors = 11
Number of Staircases = 12
Number of Exits = 1
Number of Links = 22
Number of People = 168
----------------------------------------------
Floor 0 (DXF file : geoff.dxf)
Number of People Initially in This Floor = 14
Link 1 : (17.20,1.43 m), 0.00 degrees, 0.70 m wide, connected to
Staircase 0
Exit 1 : (20.50,2.10 m), 0.00 degrees, 0.80 m wide
----------------------------------------------
Floor 1 (DXF file : geoff.dxf)
Number of People Initially in This Floor = 14
Link 2 : (16.90,2.70 m), 90.00 degrees, 0.70 m wide, connected to
Staircase 0
Link 3 : (19.10,0.80 m), -90.00 degrees, 0.70 m wide, connected to
Staircase 1
----------------------------------------------
Floor 2 (DXF file : geoff.dxf)
Number of People Initially in This Floor = 14
Link 4 : (16.92,2.93 m), 90.00 degrees, 0.70 m wide, connected to
Staircase 1
Link 5 : (19.10,0.60 m), -90.00 degrees, 0.70 m wide, connected to
Staircase 2
----------------------------------------------
Floor 3 (DXF file : geoff.dxf)
Number of People Initially in This Floor = 14
Link 6 : (16.90,2.70 m), 88.83 degrees, 0.70 m wide, connected to
Staircase 2
Link 7 : (19.70,0.30 m), -90.00 degrees, 0.70 m wide, connected to
Staircase 3
----------------------------------------------
Floor 4 (DXF file : geoff.dxf)
Number of People Initially in This Floor = 14
Link 8 : (17.30,2.96 m), 90.84 degrees, 0.70 m wide, connected to
Staircase 3
Link 9 : (19.38,0.30 m), -90.00 degrees, 1.00 m wide, connected to
Staircase 4
----------------------------------------------
Floor 5 (DXF file : geoff.dxf)
Number of People Initially in This Floor = 14
Link 10 : (16.65,2.95 m), 90.00 degrees, 0.70 m wide, connected to
Staircase 4
Link 11 : (19.70,0.70 m), -90.00 degrees, 0.70 m wide, connected to
Staircase 5
----------------------------------------------
Floor 6 (DXF file : geoff.dxf)
Number of People Initially in This Floor = 14
Link 12 : (16.90,2.80 m), 90.00 degrees, 0.70 m wide, connected to
Staircase 5
Link 13 : (19.80,0.50 m), -90.00 degrees, 0.70 m wide, connected to
Staircase 6
----------------------------------------------
Floor 7 (DXF file : geoff.dxf)
```

```
Number of People Initially in This Floor = 14
Link 14 : (16.90,2.90 m), 92.73 degrees, 0.70 m wide, connected to
Staircase 6
Link 15 : (19.10,0.60 m), -90.00 degrees, 0.70 m wide, connected to
Staircase 8
------------------------------------------------
Floor 8 (DXF file : geoff.dxf)
Number of People Initially in This Floor = 14
Link 16 : (16.80,2.70 m), 85.91 degrees, 0.70 m wide, connected to
Staircase 8
Link 17 : (19.40,0.60 m), -90.00 degrees, 0.70 m wide, connected to
Staircase 9
------------------------------------------------
Floor 9 (DXF file : geoff.dxf)
Number of People Initially in This Floor = 14
Link 18 : (17.20,2.60 m), 90.00 degrees, 0.70 m wide, connected to
Staircase 9
Link 19 : (19.80,0.90 m), -90.00 degrees, 0.70 m wide, connected to
Staircase 10
------------------------------------------------
Floor 10 (DXF file : geoff.dxf)
Number of People Initially in This Floor = 14
Link 20 : (17.30,2.60 m), 90.00 degrees, 0.70 m wide, connected to
Staircase 10
Link 21 : (19.30,0.80 m), -83.66 degrees, 0.70 m wide, connected to
Staircase 11
------------------------------------------------
Floor 11 (DXF file : geoff.dxf)
Number of People Initially in This Floor = 14
Link 22 : (16.80,2.50 m), 90.00 degrees, 0.70 m wide, connected to
Staircase 11
------------------------------------------------
Staircase 1 (1.50 m X 12.00 m)
Number of People Initially in This Stair = 0
Link 3 : (0.75,0.00 m), 270.00 degrees, 0.70 m wide, connected to
Floor 1
Link 4 : (0.65,12.00 m), 90.00 degrees, 0.70 m wide, connected to
Floor 2
------------------------------------------------
Staircase 0 (1.50 m X 12.00 m)
Number of People Initially in This Stair = 0
Link 1 : (0.80,0.00 m), 270.00 degrees, 0.70 m wide, connected to
Floor 0
Link 2 : (0.80,12.00 m), 90.00 degrees, 0.70 m wide, connected to
Floor 1
------------------------------------------------
Staircase 2 (1.50 m X 12.00 m)
Number of People Initially in This Stair = 0
Link 5 : (0.70,0.00 m), 270.00 degrees, 0.70 m wide, connected to
Floor 2
Link 6 : (0.80,12.00 m), 90.00 degrees, 0.70 m wide, connected to
Floor 3
------------------------------------------------
Staircase 3 (1.50 m X 12.00 m)
Number of People Initially in This Stair = 0
Link 7 : (0.90,0.00 m), 270.00 degrees, 0.70 m wide, connected to
Floor 3
Link 8 : (0.75,12.00 m), 90.00 degrees, 0.70 m wide, connected to
Floor 4
------------------------------------------------
Staircase 4 (1.50 m X 12.00 m)
```

```
Number of People Initially in This Stair = 0
Link 9 : (0.80,0.00 m), 270.00 degrees, 1.00 m wide, connected to
Floor 4
Link 10 : (0.75,12.00 m), 90.00 degrees, 0.70 m wide, connected to
Floor 5
-----------------------------------------------
Staircase 5 (1.50 m X 12.00 m)
Number of People Initially in This Stair = 0
Link 11 : (0.75,0.00 m), 270.00 degrees, 0.70 m wide, connected to
Floor 5
Link 12 : (0.80,12.00 m), 90.00 degrees, 0.70 m wide, connected to
Floor 6
-----------------------------------------------
Staircase 6 (1.50 m X 12.00 m)
Number of People Initially in This Stair = 0
Link 13 : (0.95,0.00 m), 270.00 degrees, 0.70 m wide, connected to
Floor 6
Link 14 : (0.80,12.00 m), 90.00 degrees, 0.70 m wide, connected to
Floor 7
-----------------------------------------------
Staircase 7 (1.50 m X 12.00 m)
Number of People Initially in This Stair = 0
-----------------------------------------------
Staircase 8 (1.50 m X 12.00 m)
Number of People Initially in This Stair = 0
Link 15 : (0.75,0.00 m), 270.00 degrees, 0.70 m wide, connected to
Floor 7
Link 16 : (0.90,12.00 m), 90.00 degrees, 0.70 m wide, connected to
Floor 8
-----------------------------------------------
Staircase 9 (1.50 m X 12.00 m)
Number of People Initially in This Stair = 0
Link 17 : (0.55,0.00 m), 270.00 degrees, 0.70 m wide, connected to
Floor 8
Link 18 : (0.75,12.00 m), 90.00 degrees, 0.70 m wide, connected to
Floor 9
-----------------------------------------------
Staircase 10 (1.50 m X 12.00 m)
Number of People Initially in This Stair = 0
Link 19 : (0.85,0.00 m), 270.00 degrees, 0.70 m wide, connected to
Floor 9
Link 20 : (0.70,12.00 m), 90.00 degrees, 0.70 m wide, connected to
Floor 10
-----------------------------------------------
Staircase 11 (1.50 m X 12.00 m)
Number of People Initially in This Stair = 0
Link 21 : (0.95,0.00 m), 270.00 degrees, 0.70 m wide, connected to
Floor 10
Link 22 : (0.95,12.00 m), 90.00 degrees, 0.70 m wide, connected to
Floor 11
-----------------------------------------------
All people reached the exit in 14:33.7.
```

13 Appendix D; Simulation and Analyses Spreadsheets for Building 1.

1. Severity calculations
2. Raw temperature and severity output data
3. Time versus temperature plot
4. Fire severity plot
5. Simple escape model for Scenario 1
6. Simple escape model for Scenario 2
7. Simple escape model for Scenario 3
8. Simple escape model for Scenario 4
9. Table of results

Fire Severity Calculations

l_1	8	,Length of room (m)
l_2	5	,Breadth of room (m)
l_3	2.4	,Height of room (m)
A_f	40	,Floor area (m^2)
e_f	300	,Fuel load energy density(MJ/m^2)
e_t	84.3	,Fuel load for total surface area (MJ/m^2)

H_v	2.00	,Height of window opening (m)
B	2.50	,Breadth of window opening (m)
A_t	142.4	,Total internal area of room (m^2)
A_v	5	,Window area (m^2)
Initial Temp	20	°C

For the Eurocode curve:

b_{gypsum}	488	,Themal Inertia ($Ws^{0.5}/m^2K$)		
F_v	0.049656	,Ventilation Factor ($m^{0.5}$)		
υ	8.707759			
t_d	0.220617	Hrs or	13.24	min
Decay rate	5.21	°C per 0.5 minutes if t_d < 30min		
or	2.08	°C per 0.5 minutes if t_d > 30min		
=	5.21			

Emissivity, υ 1 (=1 consevatively)

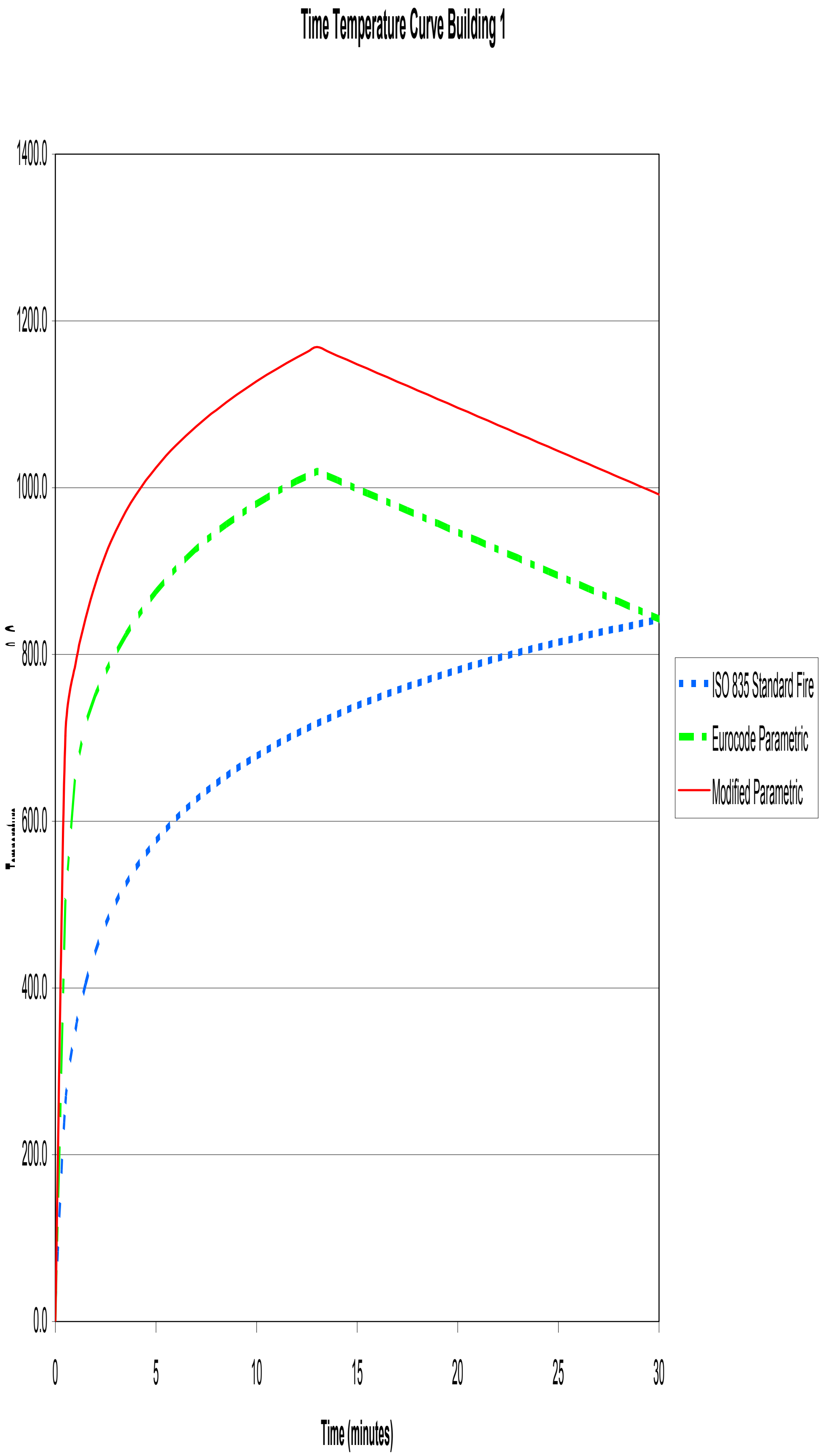
Stefan Boltzman constant, σ 5.67E-08 $W/m^2.K^4$

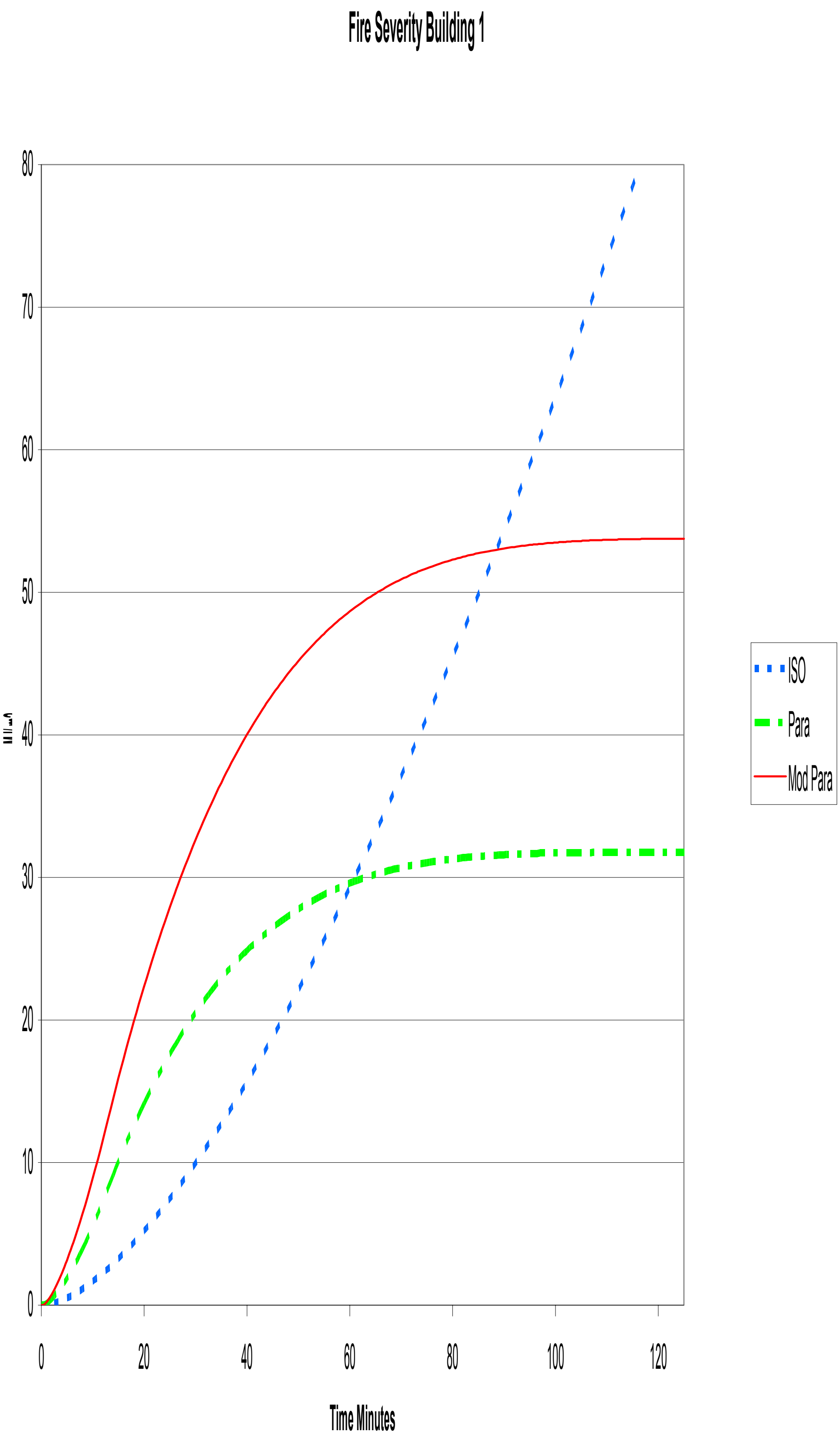
For the modified Parametric curve:

υ	23.36133	
Decay rate	5.21	°C per 0.5 minutes if t_d < 30min
or	2.08	°C per 0.5 minutes if t_d > 30min
=	5.21	

			Sevirty
			MJ/m^2
Design FRR	**30**	*min*	9.946
Actaul Time To Failure, Eurocode Fire	14.5	*min*	9.596
Actaul Time To Failure, Modified Eurocode Fire	10.5	*min*	9.547

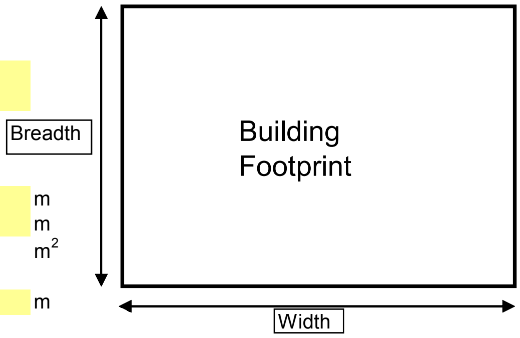
	ISO Fire			Eurocode				Modified Eurocode				
Time	Temp		Severity	t*	Temp		Severity	t*	Temp		Severity	Time
Min	°C	°K	MJ/m²	-	°C	°K	MJ/m²	-	°C	°K	MJ/m²	Min
0	20.0	293.0	0	0	0	273.0	0	0	0	273.0	0	0
0.5	261.1	534.1	0.004976	0.0725647	505.4175	778.4	0.012992	0.194678	702.4742	975.5	0.025828706	0.5
1	349.2	622.2	0.023985	0.1451293	657.0967	930.1	0.103578	0.389356	788.0393	1061.0	0.208694951	1
1.5	404.3	677.3	0.054305	0.217694	717.3033	990.3	0.248172	0.584033	842.8671	1115.9	0.447444941	1.5
2	444.5	717.5	0.094544	0.2902586	752.3697	1025.4	0.423667	0.778711	885.6813	1158.7	0.731999184	2
2.5	476.2	749.2	0.143738	0.3628233	779.2418	1052.2	0.621748	0.973389	919.9787	1193.0	1.057148233	2.5
3	502.3	775.3	0.201156	0.4353879	802.398	1075.4	0.839607	1.168067	948.0295	1221.0	1.418174897	3
3.5	524.5	797.5	0.266213	0.5079526	823.1515	1096.2	1.076016	1.362744	971.4634	1244.5	1.811000068	3.5
4	543.9	816.9	0.338431	0.5805172	841.9973	1115.0	1.330146	1.557422	991.4557	1264.5	2.232241357	4
4.5	561.0	834.0	0.417405	0.6530819	859.2049	1132.2	1.601261	1.7521	1008.855	1281.9	2.679161817	4.5
5	576.4	849.4	0.502789	0.7256465	874.9705	1148.0	1.888641	1.946778	1024.277	1297.3	3.149574447	5
5.5	590.4	863.4	0.59428	0.7982112	889.4569	1162.5	2.191579	2.141455	1038.166	1311.2	3.641738488	5.5
6	603.1	876.1	0.691612	0.8707759	902.8056	1175.8	2.509382	2.336133	1050.847	1323.8	4.154264107	6
6.5	614.9	887.9	0.794549	0.9433405	915.141	1188.1	2.841379	2.530811	1062.557	1335.6	4.686031588	6.5
7	625.8	898.8	0.902878	1.0159052	926.5731	1199.6	3.186931	2.725489	1073.47	1346.5	5.236125947	7
7.5	635.9	908.9	1.016407	1.0884698	937.199	1210.2	3.545431	2.920166	1083.716	1356.7	5.803785592	7.5
8	645.5	918.5	1.13496	1.1610345	947.1049	1220.1	3.916305	3.114844	1093.389	1366.4	6.388362836	8
8.5	654.4	927.4	1.258378	1.2335991	956.3668	1229.4	4.299019	3.309522	1102.564	1375.6	6.989293986	8.5
9	662.8	935.8	1.386513	1.3061638	965.0524	1238.1	4.693073	3.5042	1111.296	1384.3	7.60607697	9
9.5	670.8	943.8	1.519229	1.3787284	973.2211	1246.2	5.098005	3.698878	1119.627	1392.6	8.238254759	9.5
10	678.4	951.4	1.656401	1.4512931	980.9261	1253.9	5.513386	3.893555	1127.592	1400.6	8.885403218	10
10.5	685.6	958.6	1.797912	1.5238577	988.214	1261.2	5.938821	4.088233	1135.218	1408.2	9.547122286	10.5
11	692.5	965.5	1.94365	1.5964224	995.1265	1268.1	6.373945	4.282911	1142.528	1415.5	10.22302964	11
11.5	699.1	972.1	2.093515	1.6689871	1001.7	1274.7	6.818424	4.477589	1149.542	1422.5	10.91275619	11.5
12	705.4	978.4	2.24741	1.7415517	1007.968	1281.0	7.271951	4.672266	1156.275	1429.3	11.61594297	12
12.5	711.5	984.5	2.405244	1.8141164	1013.959	1287.0	7.734241	4.866944	1162.741	1435.7	12.33223896	12.5
13	717.3	990.3	2.566932	1.886681	1019.698	1292.7	8.205036	5.061622	1168.954	1442.0	13.06129969	13
13.5	722.9	995.9	2.732394	1.9592457	1014.49	1287.5	8.676219	5.2563	1163.746	1436.7	13.7913791	13.5
14	728.3	1001.3	2.901551	2.0318103	1009.281	1282.3	9.139839	5.450977	1158.538	1431.5	14.51094847	14
14.5	733.5	1006.5	3.074333	2.104375	1004.073	1277.1	9.595987	5.645655	1153.329	1426.3	15.22012168	14.5
15	738.6	1011.6	3.250669	2.1769396	998.8646	1271.9	10.04475	5.840333	1148.121	1421.1	15.9190118	15
15.5	743.4	1016.4	3.430495	2.2495043	993.6563	1266.7	10.48623	6.035011	1142.913	1415.9	16.60773105	15.5
16	748.2	1021.2	3.613747	2.3220689	988.448	1261.4	10.9205	6.229689	1137.704	1410.7	17.28639087	16
16.5	752.7	1025.7	3.800366	2.3946336	983.2396	1256.2	11.34767	6.424366	1132.496	1405.5	17.95510184	16.5
17	757.2	1030.2	3.990295	2.4671983	978.0313	1251.0	11.7678	6.619044	1127.288	1400.3	18.61397376	17
17.5	761.5	1034.5	4.183478	2.5397629	972.823	1245.8	12.181	6.813722	1122.079	1395.1	19.2631156	17.5
18	765.7	1038.7	4.379863	2.6123276	967.6146	1240.6	12.58734	7.0084	1116.871	1389.9	19.90263553	18
18.5	769.7	1042.7	4.579401	2.6848922	962.4063	1235.4	12.98692	7.203077	1111.663	1384.7	20.53264091	18.5
19	773.7	1046.7	4.782042	2.7574569	957.198	1230.2	13.37982	7.397755	1106.454	1379.5	21.15323832	19
19.5	777.6	1050.6	4.98774	2.8300215	951.9896	1225.0	13.76612	7.592433	1101.246	1374.2	21.7645335	19.5
20	781.4	1054.4	5.19645	2.9025862	946.7813	1219.8	14.1459	7.787111	1096.038	1369.0	22.36663143	20
20.5	785.0	1058.0	5.408129	2.9751508	941.573	1214.6	14.51925	7.981788	1090.829	1363.8	22.95963629	20.5
21	788.6	1061.6	5.622736	3.0477155	936.3646	1209.4	14.88626	8.176466	1085.621	1358.6	23.54365146	21
21.5	792.1	1065.1	5.84023	3.1202801	931.1563	1204.2	15.24699	8.371144	1080.413	1353.4	24.11877954	21.5
22	795.6	1068.6	6.060572	3.1928448	925.948	1198.9	15.60154	8.565822	1075.204	1348.2	24.68512234	22
22.5	798.9	1071.9	6.283726	3.2654095	920.7396	1193.7	15.94998	8.760499	1069.996	1343.0	25.2427809	22.5
23	802.2	1075.2	6.509655	3.3379741	915.5313	1188.5	16.29239	8.955177	1064.788	1337.8	25.79185549	23
23.5	805.4	1078.4	6.738324	3.4105388	910.323	1183.3	16.62885	9.149855	1059.579	1332.6	26.33244557	23.5
24	808.5	1081.5	6.969699	3.4831034	905.1146	1178.1	16.95944	9.344533	1054.371	1327.4	26.86464986	24
24.5	811.6	1084.6	7.203747	3.5556681	899.9063	1172.9	17.28424	9.539211	1049.163	1322.2	27.38856631	24.5
25	814.6	1087.6	7.440436	3.6282327	894.698	1167.7	17.60332	9.733888	1043.954	1317.0	27.90429208	25
25.5	817.6	1090.6	7.679736	3.7007974	889.4896	1162.5	17.91675	9.928566	1038.746	1311.7	28.41192361	25.5
26	820.5	1093.5	7.921615	3.773362	884.2813	1157.3	18.22462	10.12324	1033.538	1306.5	28.91155653	26
26.5	823.3	1096.3	8.166046	3.8459267	879.073	1152.1	18.527	10.31792	1028.329	1301.3	29.40328575	26.5
27	826.1	1099.1	8.412999	3.9184913	873.8646	1146.9	18.82395	10.5126	1023.121	1296.1	29.88720542	27
27.5	828.8	1101.8	8.662448	3.991056	868.6563	1141.7	19.11556	10.70728	1017.913	1290.9	30.36340892	27.5
28	831.5	1104.5	8.914364	4.0636206	863.448	1136.4	19.4019	10.90195	1012.704	1285.7	30.8319889	28
28.5	834.1	1107.1	9.168723	4.1361853	858.2396	1131.2	19.68304	11.09663	1007.496	1280.5	31.29303727	28.5
29	836.7	1109.7	9.425499	4.20875	853.0313	1126.0	19.95904	11.29131	1002.288	1275.3	31.74664518	29
29.5	839.3	1112.3	9.684667	4.2813146	847.823	1120.8	20.22999	11.48599	997.0793	1270.1	32.19290306	29.5
30	841.8	1114.8	9.946202	4.3538793	842.6146	1115.6	20.49595	11.68067	991.8709	1264.9	32.63190059	30
30.5	844.3	1117.3	10.21008	4.4264439	837.4063	1110.4	20.75698	11.87534	986.6626	1259.7	33.06372673	30.5
31	846.7	1119.7	10.47628	4.4990086	832.198	1105.2	21.01317	12.07002	981.4543	1254.5	33.4884697	31
31.5	849.1	1122.1	10.74478	4.5715732	826.9896	1100.0	21.26457	12.2647	976.2459	1249.2	33.90621699	31.5
32	851.4	1124.4	11.01556	4.6441379	821.7813	1094.8	21.51125	12.45938	971.0376	1244.0	34.31705539	32
32.5	853.7	1126.7	11.28859	4.7167025	816.573	1089.6	21.75329	12.65405	965.8293	1238.8	34.72107094	32.5
33	856.0	1129.0	11.56386	4.7892672	811.3646	1084.4	21.99074	12.84873	960.6209	1233.6	35.11834899	33
33.5	858.3	1131.3	11.84135	4.8618318	806.1563	1079.2	22.22367	13.04341	955.4126	1228.4	35.50897414	33.5
34	860.5	1133.5	12.12102	4.9343965	800.948	1073.9	22.45215	13.23809	950.2043	1223.2	35.89303032	34
34.5	862.7	1135.7	12.40288	5.0069612	795.7396	1068.7	22.67624	13.43277	944.9959	1218.0	36.27060072	34.5
35	864.8	1137.8	12.68689	5.0795258	790.5313	1063.5	22.896	13.62744	939.7876	1212.8	36.64176784	35


Time Temperature Curve Building 1
1400.0
1200.0
1000.0
800.0
600.0
400.0
200.0
0.0
0
5
10
15
20
25
30
Time (minutes)
ISO 835 Standard Fire
Eurocode Parametric
Modified Parametric


Fire Severity Building 1
80
70
60
50
40
30
20
10
0
0
20
40
60
80
100
120
Time Minutes
ISO
Para
Mod Para

Simplified Escape Model   Scenario 1

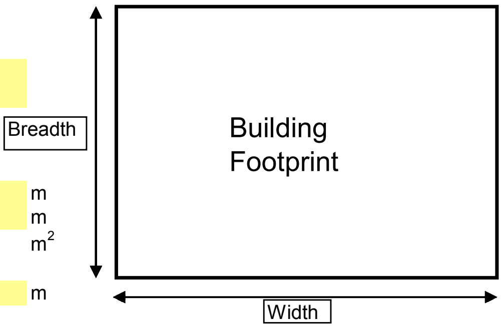
This simplified escape model assumes that the time taken to evacuate a multi-storey building with a single stair is dependant on the time taken by the last person on the top floor to exit the building. It assumes that exit geometries do not vary from floor to floor and that the evacuation of each sucessive floor is delayed by the time taken for the floor below it to travel down two flights of stairs. Further assumptions are as stated.



Design Data			
Number floors	11		
Occupants per floor	14		
Building total	154		
Breadth of building	21	m	
Width of building	21	m	
Floor area	441	m^2	
Length of each run of stairs	12	m	
Speed around floor, S_f	73	m/min uncongested	
Stair decent speed, S_s	30	m/min	
Longest travel path to exit	27	m	
Queuing Delays			
Width of stairway exit, W_{ex}	0.78	m	
Width of boundary layer, B	0.05	m	
Effective width, We	0.68	m	
Occupant density, D_o	0.031746	people/m^2	
Specific flow through door, Fs	65.0	people/min/m	
Actual flow through door, Fa	44.2	people/min	
Queuing time, tq	0.3	minutes	
Reaction times			
Time from ignition till detection	0.5	min	With Alarms opperational
Time from detection till alarm	0.1	min	
Time until occupants decide to respond	0.5	min, (from time of alarm)	
Time for occupants to investigate the fire	0.5	min, (collect belongings, fight the fire etc)	
Total time to react to fire	1.6	min	
Output			
Time taken to evacuate the building, t*	15.00	minutes	
Time until stairs penetrated by ISO fire	30	min	
Time until stairs penetrated by Eurocode fire	14.5	min	
Time until stairs penetrated by Mod. Eurocode fire	10.5	min	
ISO Fire factor of safety	2.00		
Eurocode factor of safety	0.97		
Mod. Eurocode factor of safety	0.70		
Floors unable to be evacuated, Euro	1		
Floors unable to be evacuated, Euro	4		

Simplified Escape Model   Scenario 2

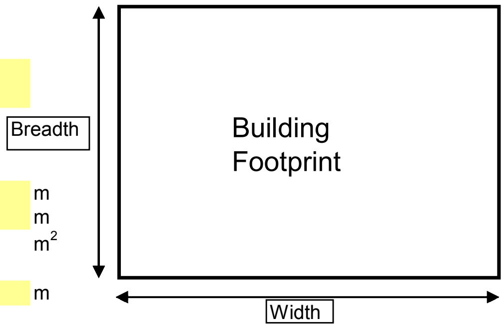
This simplified escape model assumes that the time taken to evacuate a multi-storey building with a single stair is dependant on the time taken by the last person on the top floor to exit the building. It assumes that exit geometries do not vary from floor to floor and that the evacuation of each sucessive floor is delayed by the time taken for the floor below it to travel down two flights of stairs. Further assumptions are as stated.



Design Data		
Number floors	11	
Occupants per floor	14	
Building total	154	
Breadth of building	21	m
Width of building	21	m
Floor area	441	m^2
Length of each run of stairs	12	m
Speed around floor, S_f	36.5	m/min in the dark
Stair decent speed, S_s	15	m/min in the dark
Longest travel path to exit	27	m
Queuing Delays		
Width of stairway exit, W_{ex}	0.78	m
Width of boundary layer, B	0.05	m
Effective width, We	0.68	m
Occupant density, D_o	0.031746	people/m^2
Specific flow through door, Fs	65.0	people/min/m
Actual flow through door, Fa	44.2	people/min
Queuing time, tq	0.3	minutes
Reaction times		
Time from ignition till detection	0.5	min — With Alarms opperational
Time from detection till alarm	0.1	min
Time until occupants decide to respond	0.5	min, (from time of alarm)
Time for occupants to investigate the fire	0.5	min, (collect belongings, fight the fire etc)
Total time to react to fire	1.6	min
Output		
Time taken to evacuate the building, t*	27.77	minutes
Time until stairs penetrated by ISO fire	30	min
Time until stairs penetrated by Eurocode fire	14.5	min
Time until stairs penetrated by Mod. Eurocode fire	10.5	min
ISO Fire factor of safety	1.08	
Eurocode factor of safety	0.52	
Mod. Eurocode factor of safety	0.38	
Floors unable to be evacuated, Euro	6	
Floors unable to be evacuated, Euro	8	

Simplified Escape Model Scenario 3

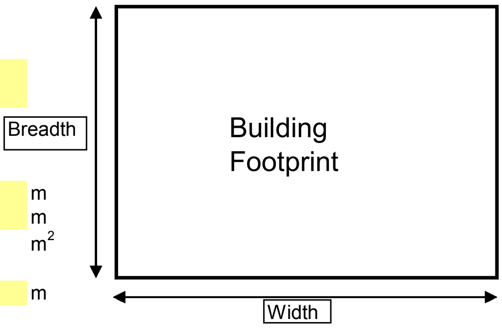
This simplified escape model assumes that the time taken to evacuate a multi-storey building with a single stair is dependant on the time taken by the last person on the top floor to exit the building. It assumes that exit geometries do not vary from floor to floor and that the evacuation of each sucessive floor is delayed by the time taken for the floor below it to travel down two flights of stairs. Further assumptions are as stated.



Design Data			
Number floors	11		
Occupants per floor	14		
Building total	154		
Breadth of building	21	m	
Width of building	21	m	
Floor area	441	m^2	
Length of each run of stairs	12	m	
Speed around floor, S_f	36.5	m/min in the dark	
Stair decent speed, S_s	15	m/min in the dark	
Longest travel path to exit	27	m	
Queuing Delays			
Width of stairway exit, W_{ex}	0.78	m	
Width of boundary layer, B	0.05	m	
Effective width, We	0.68	m	
Occupant density, D_o	0.031746	people/m^2	
Specific flow through door, Fs	65.0	people/min/m	
Actual flow through door, Fa	44.2	people/min	
Queuing time, tq	0.3	minutes	
Reaction times			
Time from ignition till detection	0.5	min	No alarms
Time from detection till alarm	0.0	min	
Time until occupants decide to respond	0.0	min, (from time of alarm)	
Time for occupants to investigate the fire	5.0	min, (collect belongings, fight the fire etc)	
Total time to react to fire	5.5	min	
			*Assume that without alarms it takes five minutes for people to realise that there is a problem
Output			
Time taken to evacuate the building, t*	31.67	minutes	
Time until stairs penetrated by ISO fire	30	min	
Time until stairs penetrated by Eurocode fire	14.5	min	
Time until stairs penetrated by Mod. Eurocode fire	10.5	min	
ISO Fire factor of safety	0.95		
Eurocode factor of safety	0.46		
Mod. Eurocode factor of safety	0.33		
Floors unable to be evacuated, Euro	8		
Floors unable to be evacuated, Euro	9		

Simplified Escape Model   Scenario 4

This simplified escape model assumes that the time taken to evacuate a multi-storey building with a single stair is dependant on the time taken by the last person on the top floor to exit the building. It assumes that exit geometries do not vary from floor to floor and that the evacuation of each sucessive floor is delayed by the time taken for the floor below it to travel down two flights of stairs. Further assumptions are as stated.



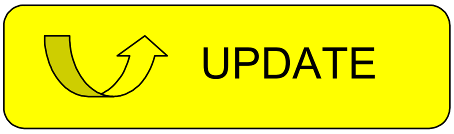
Design Data			
Number floors	11		
Occupants per floor	14		
Building total	154		
Breadth of building	21	m	
Width of building	21	m	
Floor area	441	m^2	
Length of each run of stairs	12	m	
Speed around floor, S_f	73	m/min uncongested	
Stair decent speed, S_s	30	m/min	
Longest travel path to exit	27	m	
Queuing Delays			
Width of stairway exit, W_{ex}	0.78	m	
Width of boundary layer, B	0.05	m	
Effective width, We	0.68	m	
Occupant density, D_o	0.031746	people/m^2	
Specific flow through door, Fs	65.0	people/min/m	
Actual flow through door, Fa	44.2	people/min	
Queuing time, tq	0.3	minutes	
Reaction times			
Time from ignition till detection	0.5	min	No alarms
Time from detection till alarm	0.0	min	
Time until occupants decide to respond	0.0	min, (from time of alarm)	
Time for occupants to investigate the fire	5.0	min, (collect belongings, fight the fire etc)	
Total time to react to fire	5.5	min	
			*Assume that without alarms it takes five minutes for people to realise that there is a problem
Output			
Time taken to evacuate the building, t*	18.90	minutes	
Time until stairs penetrated by ISO fire	30	min	
Time until stairs penetrated by Eurocode fire	14.5	min	
Time until stairs penetrated by Mod. Eurocode fire	10.5	min	
ISO Fire factor of safety	1.59		
Eurocode factor of safety	0.77		
Mod. Eurocode factor of safety	0.56		
Floors unable to be evacuated, Euro	4		
Floors unable to be evacuated, Euro	8		

Results - Building 1

This page contains results from the four different scenario spreadsheets. The data is collected from these sheets automatically via a macro. This macro can be run by clicking on the "update" button below. It is important that the scenario spreadsheets are not open when this macro is run!

Available escape time

ISO	30	minutes
EURO	14.5	minutes
MOD. EURO	10.5	minutes
Number of floors	11	
People per floor	14	



	Alarms and Lighting	Alarms, No lighting	No Alarms, No Lighting	No Alarms, Lighting
Total Evacuation Time	15.00	27.77	31.67	18.90
Factor of Safety	0.97	0.52	0.46	0.77
Floors unable to evac.	1	6	8	4
People at risk	14	84	112	56
Required Evac. Time	14.5	14.5	14.5	14.5

14 Appendix E; Simulation and Analyses Spreadsheets for Building 2.

1. Severity calculations
2. Raw temperature and severity output data
3. Time versus temperature plot
4. Fire severity plot
5. Simple escape model for Scenario 1
6. Simple escape model for Scenario 2
7. Simple escape model for Scenario 3
8. Simple escape model for Scenario 4
9. Table of results

Fire Severity Calculations

l_1	10	,Length of room (m)
l_2	3.5	,Breadth of room (m)
l_3	2.4	,Height of room (m)
A_f	35	,Floor area (m^2)
e_f	300	,Fuel load energy density(MJ/m^2)
e_t	77.9	,Fuel load for total surface area (MJ/m^2)

H_v	2.40	,Height of window opening (m)
B	1.50	,Breadth of window opening (m)
A_t	134.8	,Total internal area of room (m^2)
A_v	3.6	,Window area (m^2)
Initial Temp	20	°C

For the Eurocode curve;

b_{gypsum}	488	,Themal Inertia ($Ws^{0.5}/m^2K$)		
F_v	0.041373	,Ventilation Factor ($m^{0.5}$)		
	6.044951			
t_d	0.244751	Hrs or	14.69	min
Decay rate	5.21	°C per 0.5 minutes if $t_d < 30$min		
or	2.08	°C per 0.5 minutes if $t_d > 30$min		
=	5.21			

Emissivity, 1 (=1 consevatively)

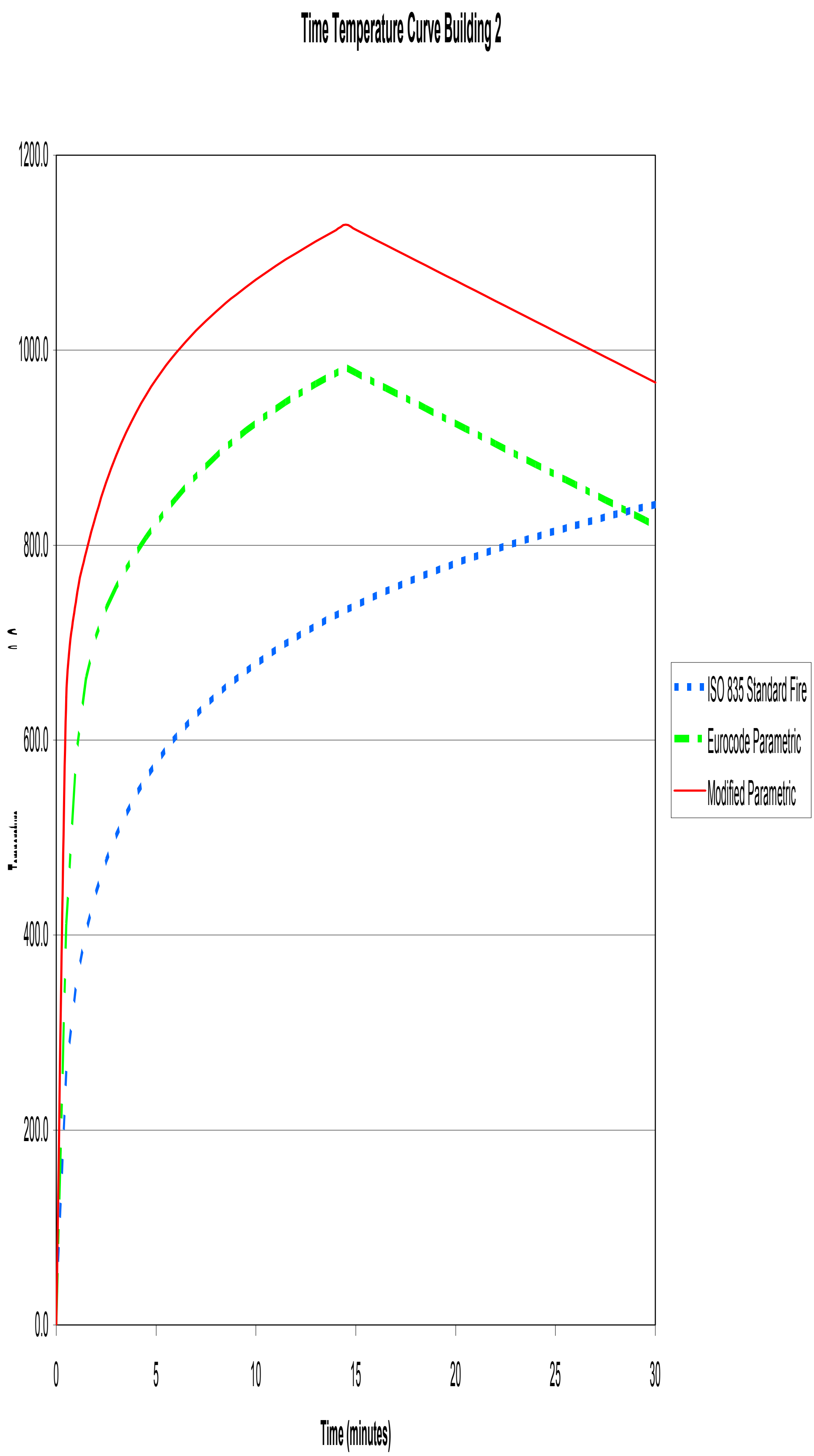
Stefan Boltzman constant, 5.67E-08 $W/m^2.K^4$

For the modified Parametric curve;

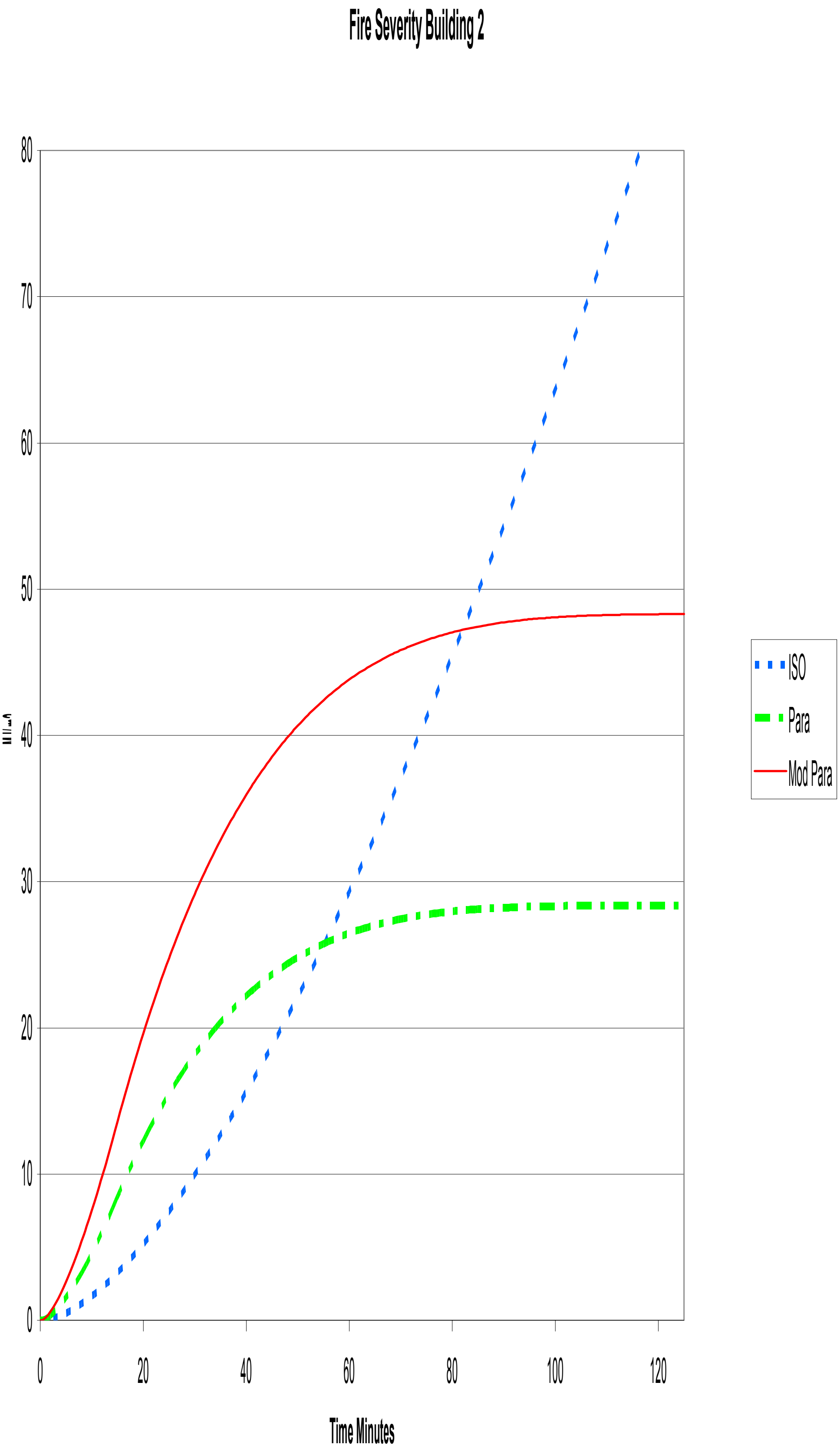
	16.2175	
Decay rate	5.21	°C per 0.5 minutes if $t_d < 30$min
or	2.08	°C per 0.5 minutes if $t_d > 30$min
=	5.21	

			Sevirty MJ/m^2
Design FRR	30	*min*	9.946
Actaul Time To Failure, Eurocode Fire	16.5	*min*	9.673
Actaul Time To Failure, Modified Eurocode Fire	12	*min*	9.820

	ISO Fire			Eurocode				Modified Eurocode				
Time	Temp		Severity	t*	Temp		Severity	t*	Temp		Severity	Time
Min	°C	°K	MJ/m^2	-	°C	°K	MJ/m^2	-	°C	°K	MJ/m^2	Min
0	20.0	293.0	0	0	0	273.0	0	0	0	273.0	0	0
0.5	261.1	534.1	0.004976	0.0503746	411.7351	684.7	0.008945	0.135146	644.3595	917.4	0.021345039	0.5
1	349.2	622.2	0.023985	0.1007492	584.2933	857.3	0.069056	0.270292	743.8894	1016.9	0.170155605	1
1.5	404.3	677.3	0.054305	0.1511238	664.0096	937.0	0.179252	0.405438	793.1761	1066.2	0.370324225	1.5
2	444.5	717.5	0.094544	0.2014984	707.1566	980.2	0.322875	0.540583	831.8434	1104.8	0.606502124	2
2.5	476.2	749.2	0.143738	0.251873	735.4163	1008.4	0.489121	0.675729	864.272	1137.3	0.875170282	2.5
3	502.3	775.3	0.201156	0.3022476	757.1821	1030.2	0.672737	0.810875	891.8648	1164.9	1.173783348	3
3.5	524.5	797.5	0.266213	0.3526222	775.739	1048.7	0.871317	0.946021	915.5788	1188.6	1.49991991	3.5
4	543.9	816.9	0.338431	0.4029968	792.4052	1065.4	1.083702	1.081167	936.1636	1209.2	1.851313953	4
4.5	561.0	834.0	0.417405	0.4533714	807.7393	1080.7	1.30924	1.216313	954.2152	1227.2	2.225910295	4.5
5	576.4	849.4	0.502789	0.5037459	822.0037	1095.0	1.54748	1.351459	970.2084	1243.2	2.621887367	5
5.5	590.4	863.4	0.59428	0.5541205	835.3432	1108.3	1.798042	1.486605	984.522	1257.5	3.037656089	5.5
6	603.1	876.1	0.691612	0.6044951	847.854	1120.9	2.060572	1.62175	997.4578	1270.5	3.47184495	6
6.5	614.9	887.9	0.794549	0.6548697	859.6099	1132.6	2.334721	1.756896	1009.257	1282.3	3.923278207	6.5
7	625.8	898.8	0.902878	0.7052443	870.6737	1143.7	2.620145	1.892042	1020.113	1293.1	4.390951613	7
7.5	635.9	908.9	1.016407	0.7556189	881.1006	1154.1	2.916501	2.027188	1030.179	1303.2	4.874008297	7.5
8	645.5	918.5	1.13496	0.8059935	890.9407	1163.9	3.223452	2.162334	1039.579	1312.6	5.371716214	8
8.5	654.4	927.4	1.258378	0.8563681	900.2396	1173.2	3.540666	2.29748	1048.413	1321.4	5.883447899	8.5
9	662.8	935.8	1.386513	0.9067427	909.0392	1182.0	3.867821	2.432626	1056.76	1329.8	6.40866274	9
9.5	670.8	943.8	1.519229	0.9571173	917.3778	1190.4	4.204603	2.567772	1064.686	1337.7	6.946891753	9.5
10	678.4	951.4	1.656401	1.0074919	925.2907	1198.3	4.550708	2.702917	1072.241	1345.2	7.497724687	10
10.5	685.6	958.6	1.797912	1.0578665	932.8102	1205.8	4.905844	2.838063	1079.469	1352.5	8.060799226	10.5
11	692.5	965.5	1.94365	1.1082411	939.966	1213.0	5.269732	2.973209	1086.405	1359.4	8.635792012	11
11.5	699.1	972.1	2.093515	1.1586157	946.7855	1219.8	5.642102	3.108355	1093.075	1366.1	9.222411246	11.5
12	705.4	978.4	2.24741	1.2089903	953.2936	1226.3	6.0227	3.243501	1099.505	1372.5	9.820390619	12
12.5	711.5	984.5	2.405244	1.2593649	959.5136	1232.5	6.411282	3.378647	1105.713	1378.7	10.42948437	12.5
13	717.3	990.3	2.566932	1.3097395	965.4665	1238.5	6.807616	3.513793	1111.715	1384.7	11.04946326	13
13.5	722.9	995.9	2.732394	1.3601141	971.1719	1244.2	7.211482	3.648939	1117.526	1390.5	11.68011135	13.5
14	728.3	1001.3	2.901551	1.4104887	976.6476	1249.6	7.622674	3.784084	1123.156	1396.2	12.32122336	14
14.5	733.5	1006.5	3.074333	1.4608632	981.9102	1254.9	8.040994	3.91923	1128.616	1401.6	12.97260262	14.5
15	738.6	1011.6	3.250669	1.5112378	976.7018	1249.7	8.45935	4.054376	1123.408	1396.4	13.62421648	15
15.5	743.4	1016.4	3.430495	1.5616124	971.4935	1244.5	8.87079	4.189522	1118.2	1391.2	14.26618092	15.5
16	748.2	1021.2	3.613747	1.611987	966.2852	1239.3	9.275399	4.324668	1112.991	1386.0	14.8986035	16
16.5	752.7	1025.7	3.800366	1.6623616	961.0768	1234.1	9.673264	4.459814	1107.783	1380.8	15.52159098	16.5
17	757.2	1030.2	3.990295	1.7127362	955.8685	1228.9	10.06447	4.59496	1102.575	1375.6	16.13524934	17
17.5	761.5	1034.5	4.183478	1.7631108	950.6602	1223.7	10.4491	4.730106	1097.366	1370.4	16.73968375	17.5
18	765.7	1038.7	4.379863	1.8134854	945.4518	1218.5	10.82723	4.865251	1092.158	1365.2	17.33499857	18
18.5	769.7	1042.7	4.579401	1.86386	940.2435	1213.2	11.19895	5.000397	1086.95	1359.9	17.92129741	18.5
19	773.7	1046.7	4.782042	1.9142346	935.0352	1208.0	11.56435	5.135543	1081.741	1354.7	18.49868305	19
19.5	777.6	1050.6	4.98774	1.9646092	929.8268	1202.8	11.9235	5.270689	1076.533	1349.5	19.06725752	19.5
20	781.4	1054.4	5.19645	2.0149838	924.6185	1197.6	12.27648	5.405835	1071.325	1344.3	19.62712205	20
20.5	785.0	1058.0	5.408129	2.0653584	919.4102	1192.4	12.62337	5.540981	1066.116	1339.1	20.17837709	20.5
21	788.6	1061.6	5.622736	2.115733	914.2018	1187.2	12.96426	5.676127	1060.908	1333.9	20.72112233	21
21.5	792.1	1065.1	5.84023	2.1661076	908.9935	1182.0	13.29922	5.811273	1055.7	1328.7	21.25545666	21.5
22	795.6	1068.6	6.060572	2.2164822	903.7852	1176.8	13.62832	5.946418	1050.491	1323.5	21.78147824	22
22.5	798.9	1071.9	6.283726	2.2668568	898.5768	1171.6	13.95165	6.081564	1045.283	1318.3	22.29928443	22.5
23	802.2	1075.2	6.509655	2.3172314	893.3685	1166.4	14.26928	6.21671	1040.075	1313.1	22.80897184	23
23.5	805.4	1078.4	6.738324	2.3676059	888.1602	1161.2	14.58129	6.351856	1034.866	1307.9	23.31063631	23.5
24	808.5	1081.5	6.969699	2.4179805	882.9518	1156.0	14.88775	6.487002	1029.658	1302.7	23.80437295	24
24.5	811.6	1084.6	7.203747	2.4683551	877.7435	1150.7	15.18873	6.622148	1024.45	1297.4	24.29027608	24.5
25	814.6	1087.6	7.440436	2.5187297	872.5352	1145.5	15.48432	6.757294	1019.241	1292.2	24.7684393	25
25.5	817.6	1090.6	7.679736	2.5691043	867.3268	1140.3	15.77457	6.89244	1014.033	1287.0	25.23895543	25.5
26	820.5	1093.5	7.921615	2.6194789	862.1185	1135.1	16.05958	7.027585	1008.825	1281.8	25.70191657	26
26.5	823.3	1096.3	8.166046	2.6698535	856.9102	1129.9	16.3394	7.162731	1003.616	1276.6	26.15741407	26.5
27	826.1	1099.1	8.412999	2.7202281	851.7018	1124.7	16.61411	7.297877	998.408	1271.4	26.60553854	27
27.5	828.8	1101.8	8.662448	2.7706027	846.4935	1119.5	16.88377	7.433023	993.1997	1266.2	27.04637985	27.5
28	831.5	1104.5	8.914364	2.8209773	841.2852	1114.3	17.14847	7.568169	987.9914	1261.0	27.48002714	28
28.5	834.1	1107.1	9.168723	2.8713519	836.0768	1109.1	17.40826	7.703315	982.783	1255.8	27.90656882	28.5
29	836.7	1109.7	9.425499	2.9217265	830.8685	1103.9	17.66322	7.838461	977.5747	1250.6	28.32609258	29
29.5	839.3	1112.3	9.684667	2.9721011	825.6602	1098.7	17.91341	7.973607	972.3664	1245.4	28.73868537	29.5
30	841.8	1114.8	9.946202	3.0224757	820.4518	1093.5	18.1589	8.108752	967.158	1240.2	29.14443342	30
30.5	844.3	1117.3	10.21008	3.0728503	815.2435	1088.2	18.39975	8.243898	961.9497	1234.9	29.54342227	30.5
31	846.7	1119.7	10.47628	3.1232249	810.0352	1083.0	18.63604	8.379044	956.7414	1229.7	29.93573671	31
31.5	849.1	1122.1	10.74478	3.1735995	804.8268	1077.8	18.86783	8.51419	951.533	1224.5	30.32146083	31.5
32	851.4	1124.4	11.01556	3.2239741	799.6185	1072.6	19.09519	8.649336	946.3247	1219.3	30.70067801	32
32.5	853.7	1126.7	11.28859	3.2743487	794.4102	1067.4	19.31816	8.784482	941.1164	1214.1	31.07347093	32.5
33	856.0	1129.0	11.56386	3.3247232	789.2018	1062.2	19.53683	8.919628	935.908	1208.9	31.43992157	33
33.5	858.3	1131.3	11.84135	3.3750978	783.9935	1057.0	19.75125	9.054773	930.6997	1203.7	31.80011118	33.5
34	860.5	1133.5	12.12102	3.4254724	778.7852	1051.8	19.96149	9.189919	925.4914	1198.5	32.15412036	34
34.5	862.7	1135.7	12.40288	3.475847	773.5768	1046.6	20.1676	9.325065	920.283	1193.3	32.50202897	34.5
35	864.8	1137.8	12.68689	3.5262216	768.3685	1041.4	20.36965	9.460211	915.0747	1188.1	32.84391621	35

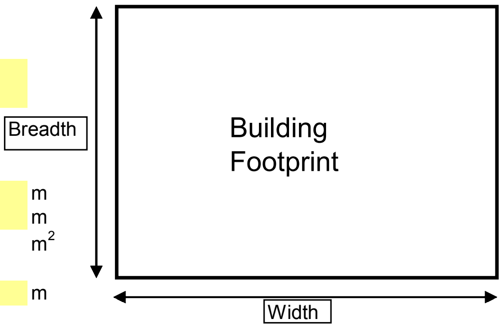


Time Temperature Curve Building 2
1200.0
1000.0
800.0
600.0
400.0
200.0
0.0
0
5
10
15
20
25
30
Time (minutes)
ISO 835 Standard Fire
Eurocode Parametric
Modified Parametric


Fire Severity Building 2
80
70
60
50
40
30
20
10
0
0
20
40
60
80
100
120
Time Minutes
ISO
Para
Mod Para

Simplified Escape Model   Scenario 1

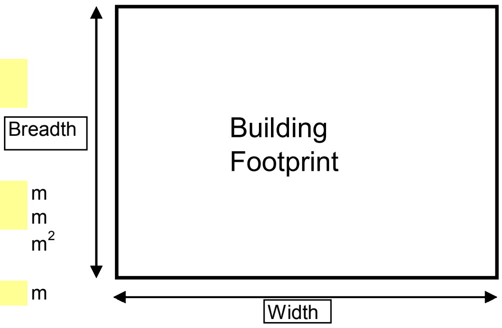
This simplified escape model assumes that the time taken to evacuate a multi-storey building with a single stair is dependant on the time taken by the last person on the top floor to exit the building. It assumes that exit geometries do not vary from floor to floor and that the evacuation of each sucessive floor is delayed by the time taken for the floor below it to travel down two flights of stairs. Further assumptions are as stated.



Design Data			
Number floors	10		
Occupants per floor	36		
Building total	360		
Breadth of building	26	m	
Width of building	21	m	
Floor area	546	m^2	
Length of each run of stairs	12	m	
Speed around floor, S_f	73	m/min uncongested	
Stair decent speed, S_s	60	m/min	
Longest travel path to exit	20	m	
Queuing Delays			
Width of stairway exit, W_{ex}	1	m	
Width of boundary layer, B	0.05	m	
Effective width, We	0.9	m	
Occupant density, D_o	0.0659341	people/m^2	
Specific flow through door, Fs	65.0	people/min/m	
Actual flow through door, Fa	58.5	people/min	
Queuing time, tq	0.6	minutes	
Reaction times			
Time from ignition till detection	0.5	min	With Alarms opperational
Time from detection till alarm	0.1	min	
Time until occupants decide to respond	0.5	min, (from time of alarm)	
Time for occupants to investigate the fire	0.5	min, (collect belongings, fight the fire etc)	
Total time to react to fire	1.6	min	
Output			
Time taken to evacuate the building, t*	8.70	minutes	
Time until stairs penetrated by ISO fire	30	min	
Time until stairs penetrated by Eurocode fire	16.5	min	
Time until stairs penetrated by Mod. Eurocode fire	12	min	
ISO Fire factor of safety	3.45		
Eurocode factor of safety	1.90		
Mod. Eurocode factor of safety	1.38		
Floors unable to be evacuated, Euro	-10		
Floors unable to be evacuated, Euro	-5		

Simplified Escape Model   Scenario 2

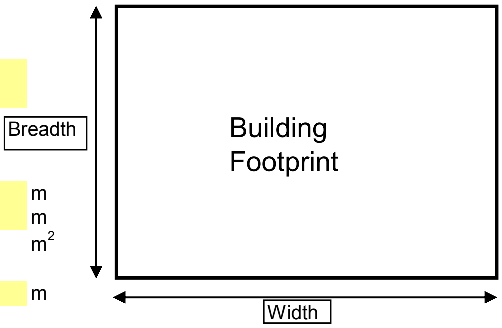
This simplified escape model assumes that the time taken to evacuate a multi-storey building with a single stair is dependant on the time taken by the last person on the top floor to exit the building. It assumes that exit geometries do not vary from floor to floor and that the evacuation of each sucessive floor is delayed by the time taken for the floor below it to travel down two flights of stairs. Further assumptions are as stated.



Design Data			
Number floors	10		
Occupants per floor	36		
Building total	360		
Breadth of building	26	m	
Width of building	21	m	
Floor area	546	m^2	
Length of each run of stairs	12	m	
Speed around floor, S_f	36.5	m/min in the dark	
Stair decent speed, S_s	30	m/min in the dark	
Longest travel path to exit	20	m	
Queuing Delays			
Width of stairway exit, W_{ex}	1	m	
Width of boundary layer, B	0.05	m	
Effective width, We	0.9	m	
Occupant density, D_o	0.0659341	people/m^2	
Specific flow through door, Fs	65.0	people/min/m	
Actual flow through door, Fa	58.5	people/min	
Queuing time, tq	0.6	minutes	
Reaction times			
Time from ignition till detection	0.5	min	With Alarms opperational
Time from detection till alarm	0.1	min	
Time until occupants decide to respond	0.5	min, (from time of alarm)	
Time for occupants to investigate the fire	0.5	min, (collect belongings, fight the fire etc)	
Total time to react to fire	1.6	min	
Output			
Time taken to evacuate the building, t*	14.58	minutes	
Time until stairs penetrated by ISO fire	30	min	
Time until stairs penetrated by Eurocode fire	16.5	min	
Time until stairs penetrated by Mod. Eurocode fire	12	min	
ISO Fire factor of safety	2.06		
Eurocode factor of safety	1.13		
Mod. Eurocode factor of safety	0.82		
Floors unable to be evacuated, Euro	-1		
Floors unable to be evacuated, Euro	3		

<u>Simplified Escape Model</u> <u>Scenario 3</u>

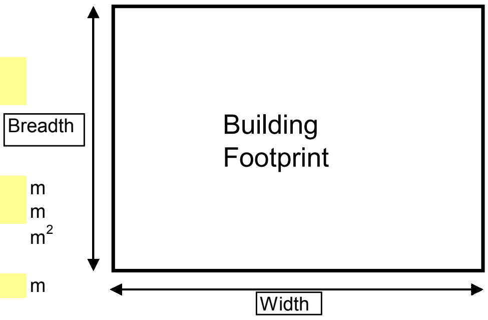
This simplified escape model assumes that the time taken to evacuate a multi-storey building with a single stair is dependant on the time taken by the last person on the top floor to exit the building. It assumes that exit geometries do not vary from floor to floor and that the evacuation of each sucessive floor is delayed by the time taken for the floor below it to travel down two flights of stairs. Further assumptions are as stated.



Design Data			
Number floors	10		
Occupants per floor	36		
Building total	360		
Breadth of building	26	m	
Width of building	21	m	
Floor area	546	m^2	
Length of each run of stairs	12	m	
Speed around floor, S_f	36.5	m/min in the dark	
Stair decent speed, S_s	30	m/min in the dark	
Longest travel path to exit	20	m	
Queuing Delays			
Width of stairway exit, W_{ex}	1	m	
Width of boundary layer, B	0.05	m	
Effective width, We	0.9	m	
Occupant density, D_o	0.0659341	people/m^2	
Specific flow through door, Fs	65.0	people/min/m	
Actual flow through door, Fa	58.5	people/min	
Queuing time, tq	0.6	minutes	
Reaction times			
Time from ignition till detection	0.5	min	No alarms
Time from detection till alarm	0.0	min	
Time until occupants decide to respond	0.0	min, (from time of alarm)	
Time for occupants to investigate the fire	5.0	min, (collect belongings, fight the fire etc)	
Total time to react to fire	5.5	min	
			*Assume that without alarms it takes five minutes for people to realise that there is a problem
Output			
Time taken to evacuate the building, t*	18.48	minutes	
Time until stairs penetrated by ISO fire	30	min	
Time until stairs penetrated by Eurocode fire	16.5	min	
Time until stairs penetrated by Mod. Eurocode fire	12	min	
ISO Fire factor of safety	1.62		
Eurocode factor of safety	0.89		
Mod. Eurocode factor of safety	0.65		
Floors unable to be evacuated, Euro	2		
Floors unable to be evacuated, Euro	6		

Simplified Escape Model   Scenario 4

This simplified escape model assumes that the time taken to evacuate a multi-storey building with a single stair is dependant on the time taken by the last person on the top floor to exit the building. It assumes that exit geometries do not vary from floor to floor and that the evacuation of each sucessive floor is delayed by the time taken for the floor below it to travel down two flights of stairs. Further assumptions are as stated.



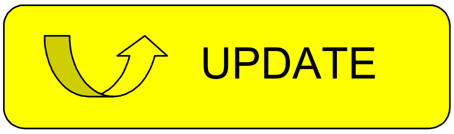
Design Data			
Number floors	10		
Occupants per floor	36		
Building total	360		
Breadth of building	26	m	
Width of building	21	m	
Floor area	546	m^2	
Length of each run of stairs	12	m	
Speed around floor, S_f	73	m/min uncongested	
Stair decent speed, S_s	60	m/min	
Longest travel path to exit	20	m	
Queuing Delays			
Width of stairway exit, W_{ex}	1	m	
Width of boundary layer, B	0.05	m	
Effective width, We	0.9	m	
Occupant density, D_o	0.0659341	people/m^2	
Specific flow through door, Fs	65.0	people/min/m	
Actual flow through door, Fa	58.5	people/min	
Queuing time, tq	0.6	minutes	
Reaction times			
Time from ignition till detection	0.5	min	No alarms
Time from detection till alarm	0.0	min	
Time until occupants decide to respond	0.0	min, (from time of alarm)	
Time for occupants to investigate the fire	5.0	min, (collect belongings, fight the fire etc)	
Total time to react to fire	5.5	min	
			*Assume that without alarms it takes
Output			five minutes for people to realise that
Time taken to evacuate the building, t*	12.60	minutes	there is a problem
Time until stairs penetrated by ISO fire	30	min	
Time until stairs penetrated by Eurocode fire	16.5	min	
Time until stairs penetrated by Mod. Eurocode fire	12	min	
ISO Fire factor of safety	2.38		
Eurocode factor of safety	1.31		
Mod. Eurocode factor of safety	0.95		
Floors unable to be evacuated, Euro	-6		
Floors unable to be evacuated, Euro	2		

Results - Building 2

This page contains results from the four different scenario spreadsheets. The data is collected from these sheets automatically via a macro. This macro can be run by clicking on the "update" button below. It is important that the scenario spreadsheets are not open when this macro is run!

Available escape time

ISO	30	minutes
EURO	16.5	minutes
MOD. EURO	12	minutes
Number of floors	10	
People per floor	36	



	Alarms and Lighting	Alarms, No lighting	No Alarms, No Lighting	No Alarms, Lighting
Total Evacuation Time	8.70	14.58	18.48	12.60
Factor of Safety	1.90	1.13	0.89	1.31
Floors unable to evac.	-10	-1	2	-6
People at risk	0	0	72	0
Available Evac. Time	16.5	16.5	16.5	16.5

15 Appendix F; Simulation and Analyses Spreadsheets for Building 3.

1. Severity calculations
2. Raw temperature and severity output data
3. Time versus temperature plot
4. Fire severity plot
5. Simple escape model for Scenario 1
6. Simple escape model for Scenario 2
7. Simple escape model for Scenario 3
8. Simple escape model for Scenario 4
9. Table of results

Fire Severity Calculations

l_1	18	,Length of room (m)	H_v	2.00	,Height of window opening (m)
l_2	26	,Breadth of room (m)	B	15.00	,Breadth of window opening (m)
l_3	2.4	,Height of room (m)	A_t	1147.2	,Total internal area of room (m^2)
A_f	468	,Floor area (m^2)	A_v	30	,Window area (m^2)
e_f	800	,Fuel load energy density(MJ/m^2)	***Initial Temp***	20	°C
e_t	326.4	,Fuel load for total surface area (MJ/m^2)			

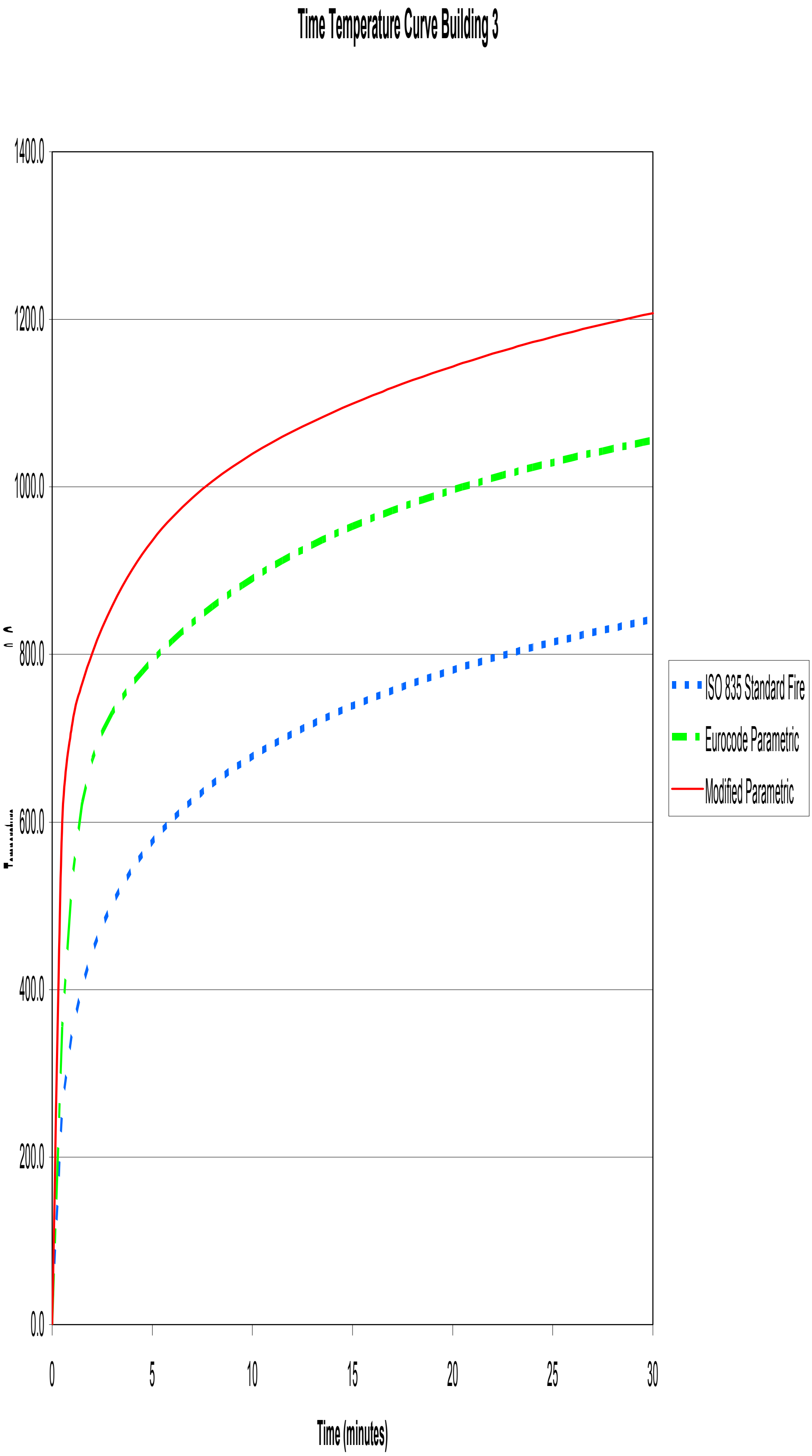
For the Eurocode curve;

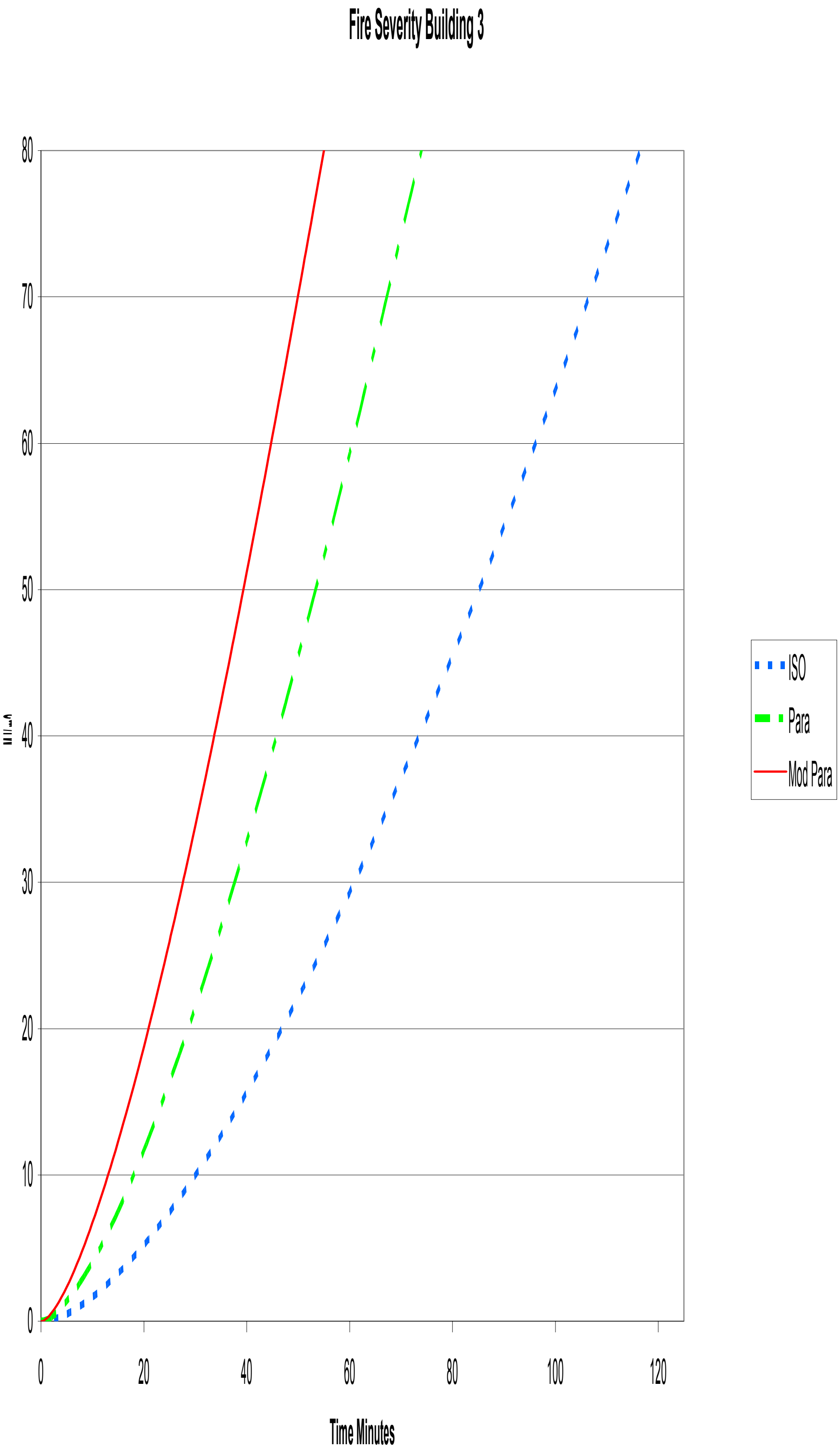
b_{gypsum}	488	,Themal Inertia ($Ws^{0.5}/m^2K$)					
F_v	0.036983	,Ventilation Factor ($m^{0.5}$)					
	4.830038						
t_d	1.14721	Hrs or 68.83 min					
Decay rate	5.21	°C per 0.5 minutes if t_d < 30min					
or	2.08	°C per 0.5 minutes if t_d > 30min			***Emissivity,***	1	(=1 consevatively)
=	2.08				***Stefan Boltzman constant,***	5.67E-08	$W/m^2.K^4$

For the modified Parametric curve;

						Sevirty
						MJ/m^2
	12.95811		*Design FRR*	30	*min*	9.946
Decay rate	5.21	°C per 0.5 minutes if t_d < 30min	*Actaul Time To Failure, Eurocode Fire*	17.5	*min*	9.530
or	2.08	°C per 0.5 minutes if t_d > 30min	*Actaul Time To Failure, Modified Eurocode Fire*	12.5	*min*	9.388
=	2.08					

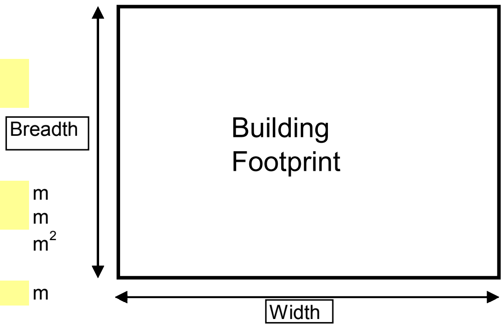
Time	ISO Fire			Eurocode				Modified Eurocode				Time
	Temp		Severity	t*	Temp		Severity	t*	Temp		Severity	
Min	°C	°K	MJ/m^2	-	°C	°K	MJ/m^2	-	°C	°K	MJ/m^2	Min
0	20.0	293.0	0	0	0	273.0	0	0	0	273.0	0	0
0.5	261.1	534.1	0.004976	0.0402503	355.628	628.6	0.007026	0.107984	599.53	872.5	0.018306703	0.5
1	349.2	622.2	0.023985	0.0805006	531.3403	804.3	0.051852	0.215969	716.28	989.3	0.146046342	1
1.5	404.3	677.3	0.054305	0.120751	622.7429	895.7	0.140662	0.323953	765.4679	1038.5	0.325784428	1.5
2	444.5	717.5	0.094544	0.1610013	674.3722	947.4	0.263348	0.431937	801.3568	1074.4	0.537639166	2
2.5	476.2	749.2	0.143738	0.2012516	706.9918	980.0	0.410051	0.539921	831.6707	1104.7	0.777321043	2.5
3	502.3	775.3	0.201156	0.2415019	730.2982	1003.3	0.574537	0.647906	858.0273	1131.0	1.042926432	3
3.5	524.5	797.5	0.266213	0.2817522	748.8345	1021.8	0.75335	0.75589	881.155	1154.2	1.332839471	3.5
4	543.9	816.9	0.338431	0.3220026	764.7433	1037.7	0.944642	0.863874	901.5815	1174.6	1.645494739	4
4.5	561.0	834.0	0.417405	0.3622529	779.0478	1052.0	1.147409	0.971859	919.736	1192.7	1.979390054	4.5
5	576.4	849.4	0.502789	0.4025032	792.249	1065.2	1.361063	1.079843	935.975	1209.0	2.333116329	5
5.5	590.4	863.4	0.59428	0.4427535	804.6026	1077.6	1.58522	1.187827	950.5958	1223.6	2.705376306	5.5
6	603.1	876.1	0.691612	0.4830038	816.249	1089.2	1.819589	1.295811	963.8462	1236.8	3.094992379	6
6.5	614.9	887.9	0.794549	0.5232542	827.2734	1100.3	2.063922	1.403796	975.9327	1248.9	3.500906652	6.5
7	625.8	898.8	0.902878	0.5635045	837.7342	1110.7	2.317987	1.51178	987.0281	1260.0	3.922176015	7
7.5	635.9	908.9	1.016407	0.6037548	847.6757	1120.7	2.581561	1.619764	997.2764	1270.3	4.357964255	7.5
8	645.5	918.5	1.13496	0.6440051	857.135	1130.1	2.854421	1.727749	1006.798	1279.8	4.80753264	8
8.5	654.4	927.4	1.258378	0.6842554	866.1443	1139.1	3.136348	1.835733	1015.694	1288.7	5.270229938	8.5
9	662.8	935.8	1.386513	0.7245058	874.7329	1147.7	3.427122	1.943717	1024.047	1297.0	5.745482513	9
9.5	670.8	943.8	1.519229	0.7647561	882.9276	1155.9	3.726526	2.051701	1031.93	1304.9	6.23278488	9.5
10	678.4	951.4	1.656401	0.8050064	890.7532	1163.8	4.034347	2.159686	1039.401	1312.4	6.73169095	10
10.5	685.6	958.6	1.797912	0.8452567	898.2328	1171.2	4.350372	2.26767	1046.509	1319.5	7.241806071	10.5
11	692.5	965.5	1.94365	0.885507	905.388	1178.4	4.674394	2.375654	1053.296	1326.3	7.762779902	11
11.5	699.1	972.1	2.093515	0.9257574	912.2389	1185.2	5.006212	2.483639	1059.799	1332.8	8.294300104	11.5
12	705.4	978.4	2.24741	0.9660077	918.8043	1191.8	5.345629	2.591623	1066.045	1339.0	8.836086808	12
12.5	711.5	984.5	2.405244	1.006258	925.1017	1198.1	5.692451	2.699607	1072.06	1345.1	9.387887793	12.5
13	717.3	990.3	2.566932	1.0465083	931.1475	1204.1	6.046495	2.807591	1077.866	1350.9	9.949474324	13
13.5	722.9	995.9	2.732394	1.0867586	936.9571	1210.0	6.407579	2.915576	1083.481	1356.5	10.52063755	13.5
14	728.3	1001.3	2.901551	1.127009	942.5446	1215.5	6.775531	3.02356	1088.919	1361.9	11.10118544	14
14.5	733.5	1006.5	3.074333	1.1672593	947.9236	1220.9	7.150182	3.131544	1094.195	1367.2	11.69094013	14.5
15	738.6	1011.6	3.250669	1.2075096	953.1066	1226.1	7.531372	3.239529	1099.319	1372.3	12.28973573	15
15.5	743.4	1016.4	3.430495	1.2477599	958.1051	1231.1	7.918946	3.347513	1104.301	1377.3	12.89741638	15.5
16	748.2	1021.2	3.613747	1.2880102	962.9302	1235.9	8.312755	3.455497	1109.15	1382.2	13.51383466	16
16.5	752.7	1025.7	3.800366	1.3282606	967.592	1240.6	8.712657	3.563481	1113.873	1386.9	14.13885027	16.5
17	757.2	1030.2	3.990295	1.3685109	972.1001	1245.1	9.118515	3.671466	1118.476	1391.5	14.77232884	17
17.5	761.5	1034.5	4.183478	1.4087612	976.4635	1249.5	9.530197	3.77945	1122.966	1396.0	15.41414102	17.5
18	765.7	1038.7	4.379863	1.4490115	980.6904	1253.7	9.94758	3.887434	1127.347	1400.3	16.06416166	18
18.5	769.7	1042.7	4.579401	1.4892618	984.7887	1257.8	10.37054	3.995419	1131.623	1404.6	16.72226917	18.5
19	773.7	1046.7	4.782042	1.5295121	988.7657	1261.8	10.79897	4.103403	1135.799	1408.8	17.38834492	19
19.5	777.6	1050.6	4.98774	1.5697625	992.6281	1265.6	11.23276	4.211387	1139.878	1412.9	18.06227287	19.5
20	781.4	1054.4	5.19645	1.6100128	996.3824	1269.4	11.6718	4.319371	1143.864	1416.9	18.74393911	20
20.5	785.0	1058.0	5.408129	1.6502631	1000.035	1273.0	12.11599	4.427356	1147.76	1420.8	19.43323161	20.5
21	788.6	1061.6	5.622736	1.6905134	1003.59	1276.6	12.56524	4.53534	1151.568	1424.6	20.13003996	21
21.5	792.1	1065.1	5.84023	1.7307637	1007.054	1280.1	13.01946	4.643324	1155.291	1428.3	20.83425514	21.5
22	795.6	1068.6	6.060572	1.7710141	1010.432	1283.4	13.47856	4.751309	1158.932	1431.9	21.54576943	22
22.5	798.9	1071.9	6.283726	1.8112644	1013.728	1286.7	13.94246	4.859293	1162.492	1435.5	22.26447619	22.5
23	802.2	1075.2	6.509655	1.8515147	1016.947	1289.9	14.41109	4.967277	1165.974	1439.0	22.99026983	23
23.5	805.4	1078.4	6.738324	1.891765	1020.091	1293.1	14.88436	5.075261	1169.38	1442.4	23.72304573	23.5
24	808.5	1081.5	6.969699	1.9320153	1023.166	1296.2	15.3622	5.183246	1172.712	1445.7	24.46270013	24
24.5	811.6	1084.6	7.203747	1.9722657	1026.175	1299.2	15.84455	5.29123	1175.972	1449.0	25.20913015	24.5
25	814.6	1087.6	7.440436	2.012516	1029.12	1302.1	16.33134	5.399214	1179.161	1452.2	25.96223375	25
25.5	817.6	1090.6	7.679736	2.0527663	1032.006	1305.0	16.82251	5.507199	1182.281	1455.3	26.72190966	25.5
26	820.5	1093.5	7.921615	2.0930166	1034.834	1307.8	17.318	5.615183	1185.333	1458.3	27.48805744	26
26.5	823.3	1096.3	8.166046	2.1332669	1037.608	1310.6	17.81775	5.723167	1188.32	1461.3	28.26057744	26.5
27	826.1	1099.1	8.412999	2.1735173	1040.33	1313.3	18.32172	5.831151	1191.243	1464.2	29.0393708	27
27.5	828.8	1101.8	8.662448	2.2137676	1043.003	1316.0	18.82984	5.939136	1194.103	1467.1	29.82433948	27.5
28	831.5	1104.5	8.914364	2.2540179	1045.629	1318.6	19.34207	6.04712	1196.901	1469.9	30.61538625	28
28.5	834.1	1107.1	9.168723	2.2942682	1048.209	1321.2	19.85836	6.155104	1199.639	1472.6	31.4124147	28.5
29	836.7	1109.7	9.425499	2.3345185	1050.746	1323.7	20.37866	6.263089	1202.319	1475.3	32.21532926	29
29.5	839.3	1112.3	9.684667	2.3747689	1053.242	1326.2	20.90294	6.371073	1204.941	1477.9	33.02403523	29.5
30	841.8	1114.8	9.946202	2.4150192	1055.698	1328.7	21.43114	6.479057	1207.507	1480.5	33.83843877	30
30.5	844.3	1117.3	10.21008	2.4552695	1058.116	1331.1	21.96324	6.587041	1210.018	1483.0	34.65844692	30.5
31	846.7	1119.7	10.47628	2.4955198	1060.498	1333.5	22.49919	6.695026	1212.475	1485.5	35.48396763	31
31.5	849.1	1122.1	10.74478	2.5357701	1062.844	1335.8	23.03895	6.80301	1214.879	1487.9	36.31490976	31.5
32	851.4	1124.4	11.01556	2.5760205	1065.157	1338.2	23.58249	6.910994	1217.232	1490.2	37.1511831	32
32.5	853.7	1126.7	11.28859	2.6162708	1067.437	1340.4	24.12977	7.018979	1219.535	1492.5	37.9926984	32.5
33	856.0	1129.0	11.56386	2.6565211	1069.686	1342.7	24.68076	7.126963	1221.789	1494.8	38.83936734	33
33.5	858.3	1131.3	11.84135	2.6967714	1071.905	1344.9	25.23544	7.234947	1223.994	1497.0	39.69110259	33.5
34	860.5	1133.5	12.12102	2.7370217	1074.095	1347.1	25.79376	7.342931	1226.152	1499.2	40.5478178	34
34.5	862.7	1135.7	12.40288	2.7772721	1076.256	1349.3	26.3557	7.450916	1228.264	1501.3	41.4094276	34.5
35	864.8	1137.8	12.68689	2.8175224	1078.39	1351.4	26.92123	7.5589	1230.331	1503.3	42.27584763	35


Time Temperature Curve Building 3
1400.0
1200.0
1000.0
800.0
600.0
400.0
200.0
0.0
0
5
10
15
20
25
30
Time (minutes)
ISO 835 Standard Fire
Eurocode Parametric
Modified Parametric


Fire Severity Building 3
80
70
60
50
40
30
20
10
0
0
20
40
60
80
100
120
Time Minutes
ISO
Para
Mod Para

Simplified Escape Model Scenario 1

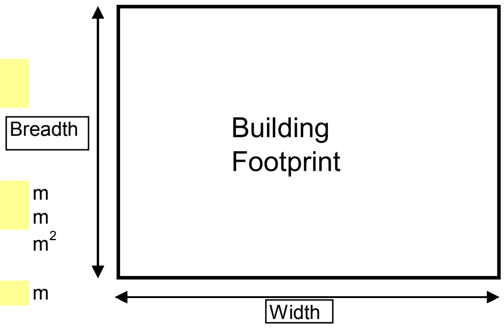
This simplified escape model assumes that the time taken to evacuate a multi-storey building with a single stair is dependant on the time taken by the last person on the top floor to exit the building. It assumes that exit geometries do not vary from floor to floor and that the evacuation of each sucessive floor is delayed by the time taken for the floor below it to travel down two flights of stairs. Further assumptions are as stated.



Design Data			
Number floors	16		
Occupants per floor	90		
Building total	1440		
Breadth of building	36	m	
Width of building	26	m	
Floor area	936	m^2	
Length of each run of stairs	12	m	
Speed around floor, S_f	73	m/min uncongested	
Stair decent speed, S_s	60	m/min	
Longest travel path to exit	20	m	
Queuing Delays			
Width of stairway exit, W_{ex}	1	m	
Width of boundary layer, B	0.05	m	
Effective width, We	0.9	m	
Occupant density, D_o	0.0961538	people/m^2	
Specific flow through door, Fs	65.0	people/min/m	
Actual flow through door, Fa	58.5	people/min	
Queuing time, tq	1.5	minutes	
Reaction times			
Time from ignition till detection	0.5	min	With Alarms opperational
Time from detection till alarm	0.1	min	
Time until occupants decide to respond	0.5	min, (from time of alarm)	
Time for occupants to investigate the fire	0.5	min, (collect belongings, fight the fire etc)	
Total time to react to fire	1.6	min	
Output			
Time taken to evacuate the building, t*	14.15	minutes	
Time until stairs penetrated by ISO fire	30	min	
Time until stairs penetrated by Eurocode fire	17.5	min	
Time until stairs penetrated by Mod. Eurocode fire	12.5	min	
ISO Fire factor of safety	2.12		
Eurocode factor of safety	1.24		
Mod. Eurocode factor of safety	0.88		
Floors unable to be evacuated, Euro	-4		
Floors unable to be evacuated, Euro	3		

Simplified Escape Model   Scenario 2

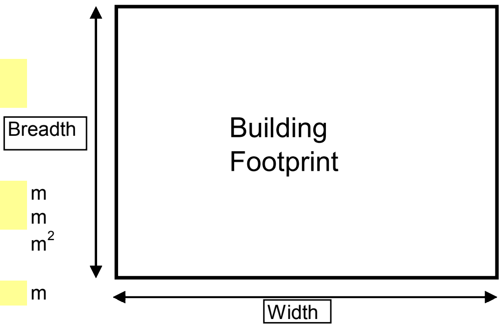
This simplified escape model assumes that the time taken to evacuate a multi-storey building with a single stair is dependant on the time taken by the last person on the top floor to exit the building. It assumes that exit geometries do not vary from floor to floor and that the evacuation of each sucessive floor is delayed by the time taken for the floor below it to travel down two flights of stairs. Further assumptions are as stated.



Design Data			
Number floors	16		
Occupants per floor	5		
Building total	80		
Breadth of building	36	m	
Width of building	26	m	
Floor area	936	m^2	
Length of each run of stairs	12	m	
Speed around floor, S_f	36.5	m/min in the dark	
Stair decent speed, S_s	30	m/min in the dark	
Longest travel path to exit	20	m	
Queuing Delays			
Width of stairway exit, W_{ex}	1	m	
Width of boundary layer, B	0.05	m	
Effective width, We	0.9	m	
Occupant density, D_o	0.0053419	people/m^2	
Specific flow through door, Fs	65.0	people/min/m	
Actual flow through door, Fa	58.5	people/min	
Queuing time, tq	0.1	minutes	
Reaction times			
Time from ignition till detection	0.5	min	With Alarms opperational
Time from detection till alarm	0.1	min	
Time until occupants decide to respond	0.5	min, (from time of alarm)	
Time for occupants to investigate the fire	0.5	min, (collect belongings, fight the fire etc)	
Total time to react to fire	1.6	min	
Output			
Time taken to evacuate the building, t*	20.72	minutes	
Time until stairs penetrated by ISO fire	30	min	
Time until stairs penetrated by Eurocode fire	17.5	min	
Time until stairs penetrated by Mod. Eurocode fire	12.5	min	
ISO Fire factor of safety	1.45		
Eurocode factor of safety	0.84		
Mod. Eurocode factor of safety	0.60		
Floors unable to be evacuated, Euro	3		
Floors unable to be evacuated, Euro	7		

Simplified Escape Model   Scenario 3

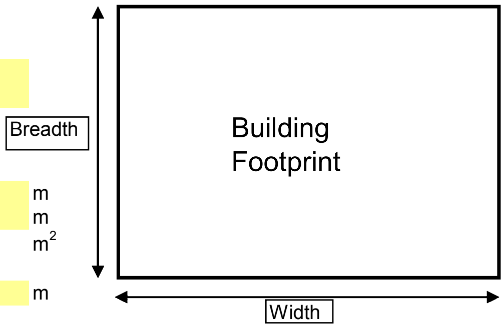
This simplified escape model assumes that the time taken to evacuate a multi-storey building with a single stair is dependant on the time taken by the last person on the top floor to exit the building. It assumes that exit geometries do not vary from floor to floor and that the evacuation of each sucessive floor is delayed by the time taken for the floor below it to travel down two flights of stairs. Further assumptions are as stated.



Design Data			
Number floors	16		
Occupants per floor	5		
Building total	80		
Breadth of building	26	m	
Width of building	36	m	
Floor area	936	m^2	
Length of each run of stairs	12	m	
Speed around floor, S_f	36.5	m/min in the dark	
Stair decent speed, S_s	30	m/min in the dark	
Longest travel path to exit	20	m	
Queuing Delays			
Width of stairway exit, W_{ex}	1	m	
Width of boundary layer, B	0.05	m	
Effective width, We	0.9	m	
Occupant density, D_o	0.0053419	people/m^2	
Specific flow through door, Fs	65.0	people/min/m	
Actual flow through door, Fa	58.5	people/min	
Queuing time, tq	0.1	minutes	
Reaction times			
Time from ignition till detection	0.5	min	No alarms
Time from detection till alarm	0.0	min	
Time until occupants decide to respond	0.0	min, (from time of alarm)	
Time for occupants to investigate the fire	8.0	min, (collect belongings, fight the fire etc)	
Total time to react to fire	8.5	min	
Output			*Assume that without alarms it takes eight minutes for people to realise that there is a problem
Time taken to evacuate the building, t*	27.62	minutes	
Time until stairs penetrated by ISO fire	30	min	
Time until stairs penetrated by Eurocode fire	17.5	min	
Time until stairs penetrated by Mod. Eurocode fire	12.5	min	
ISO Fire factor of safety	1.09		
Eurocode factor of safety	0.63		
Mod. Eurocode factor of safety	0.45		
Floors unable to be evacuated, Euro	9		
Floors unable to be evacuated, Euro	13		

Simplified Escape Model   Scenario 4

This simplified escape model assumes that the time taken to evacuate a multi-storey building with a single stair is dependant on the time taken by the last person on the top floor to exit the building. It assumes that exit geometries do not vary from floor to floor and that the evacuation of each sucessive floor is delayed by the time taken for the floor below it to travel down two flights of stairs. Further assumptions are as stated.

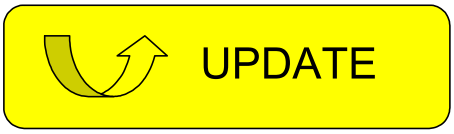


Design Data			
Number floors	16		
Occupants per floor	90		
Building total	1440		
Breadth of building	36	m	
Width of building	26	m	
Floor area	936	m^2	
Length of each run of stairs	12	m	
Speed around floor, S_f	73	m/min uncongested	
Stair decent speed, S_s	60	m/min	
Longest travel path to exit	20	m	
Queuing Delays			
Width of stairway exit, W_{ex}	1	m	
Width of boundary layer, B	0.05	m	
Effective width, We	0.9	m	
Occupant density, D_o	0.0961538	people/m^2	
Specific flow through door, Fs	65.0	people/min/m	
Actual flow through door, Fa	58.5	people/min	
Queuing time, tq	1.5	minutes	
Reaction times			
Time from ignition till detection	0.5	min	No alarms
Time from detection till alarm	0.0	min	
Time until occupants decide to respond	0.0	min, (from time of alarm)	
Time for occupants to investigate the fire	3.0	min, (collect belongings, fight the fire etc)	
Total time to react to fire	3.5	min	*Assume that without alarms it takes three minutes for people to realise that there is a problem
Output			
Time taken to evacuate the building, t*	16.05	minutes	
Time until stairs penetrated by ISO fire	30	min	
Time until stairs penetrated by Eurocode fire	17.5	min	
Time until stairs penetrated by Mod. Eurocode fire	12.5	min	
ISO Fire factor of safety	1.87		
Eurocode factor of safety	1.09		
Mod. Eurocode factor of safety	0.78		
Floors unable to be evacuated, Euro	-2		
Floors unable to be evacuated, Euro	6		

Results - Building 3

This page contains results from the four different scenario spreadsheets. The data is collected from these sheets automatically via a macro. This macro can be run by clicking on the "update" button below. It is important that the scenario spreadsheets are not open when this macro is run!

Available escape time		
ISO	30	minutes
EURO	17.5	minutes
MOD. EURO	12.5	minutes
Number of floors	16	
People per floor	90	Daytime
People per floor	5	Night time



	Alarms and Lighting	Alarms, No lighting	No Alarms, No Lighting	No Alarms, Lighting
Total Evacuation Time	14.15	20.72	27.62	16.05
Factor of Safety	1.24	0.84	0.63	1.09
Floors unable to evac.	-4	3	9	-2
People at risk	0	15	45	0
Required Evac. Time	17.5	17.5	17.5	17.5